Digitized by the Internet Archive
in 2013

http://archive.org/details/researchpaper38paci

PUBLIC DOCUMENTS
DEPOSITORY ITEM

NOV 26 1990

CLEMSON
LIBRARY

United States
Department of
Agriculture

Forest Service

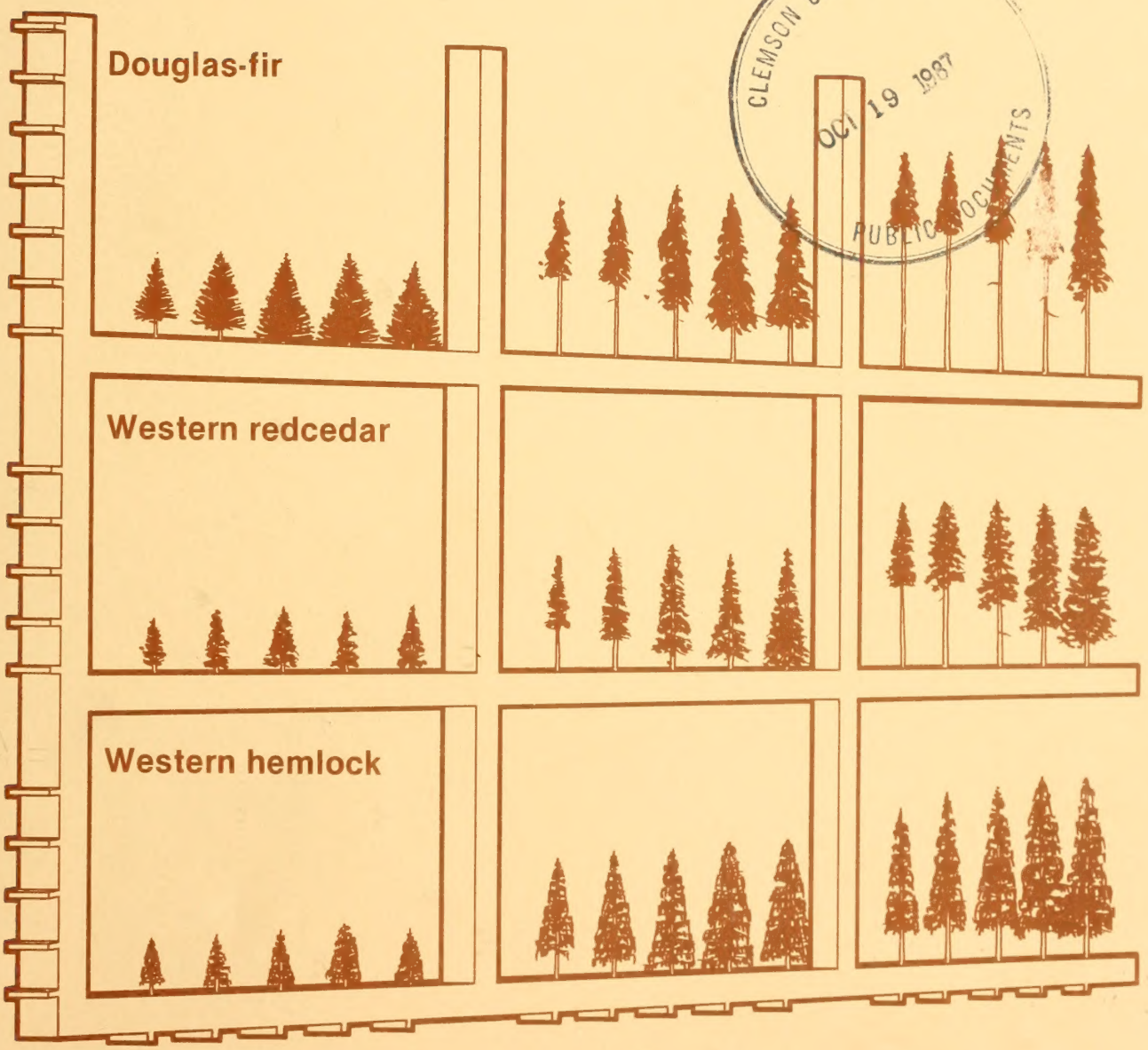
Pacific Northwest
Research Station

Research Paper
PNW-RP-381.

Development Over 25 Years of Douglas-Fir, Western Hemlock, and Western Redcedar Planted at Various Spacings on a Very Good Site in British Columbia

Donald L. Reukema and J. Harry G. Smith

CLEMSON UNIVERSITY
OCT 19 1987
PUBLIC DOCUMENTS



Authors

DONALD L. REUKEMA is principal silviculturist, Pacific Northwest Research Station, Forestry Sciences Laboratory, 3625 93d Avenue S.W., Olympia, WA 98502. J. HARRY G. SMITH is professor and head, Forest Resources Management Department, Faculty of Forestry, University of British Columbia, Vancouver, BC, Canada V6T 1W5.

Abstract

Reukema, Donald L.; Smith, J. Harry G. Development over 25 years of Douglas-fir, western hemlock, and western redcedar planted at various spacings on a very good site in British Columbia. Res. Pap. PNW-RP-381. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station; **1987.** 46 p.

Results of five spacing trials on the University of British Columbia Research Forest, covering a range of plantation spacings from 1 to 5 meters, showed that choice of initial spacing is among the most important factors influencing bole and crown development and stand growth and yield. The trials include Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western redcedar (*Thuja plicata*). The results to date should help managers to choose optimum spacings for their purposes. Initial wide spacings with rectangularities up to 2:1, such as 6 by 3 meters, resulted in efficient production of large trees of high value and satisfactory quality. Pruning of widely spaced trees to enhance quality of the lower bole is strongly recommended.

Keywords: Plantation spacing, (-growth, stand development, density, height increment, diameter increment, crown development.

Summary

Influences of plantation spacing on bole and crown development were studied in five trials established from 1957 to 1967 on a very productive site near Maple Ridge (Haney), British Columbia. Douglas-fir (*Pseudotsuga menziesii*) has grown much larger and produced more volume than western hemlock (*Tsuga heterophylla*) or western redcedar (*Thuja plicata*). The trials include spacings from 1 to 5 meters, rectangularities from 1:1 to 2:1, and some alternate rows of Douglas-fir and western hemlock. Results from 0.2-ha-plot, 49-tree-plot, rectangularity, Nelder-plot, and variable-block trials showed similar effects of spacing on growth of Douglas-fir.

Top heights were initially a little taller at close spacings because of more opportunities for natural selection of superior genotypes and microsites, but top heights are now similar at all spacings; initial advantages of natural selection for the many trees planted at close spacings have disappeared. Average heights are now shorter at close spacing. Decreases in heights to dead and live crowns and increases in diameter of lower boles, taper, and crown size occurred as spacing increased. Basal area and volumes per hectare increased as spacing decreased until onset of density-related mortality from snow damage and similar causes.

Although it is difficult to establish plantations on such productive sites because of heavy competition from brush, potential gains from initial wide spacing and pruning are impressive. The results to date should help managers to choose optimum spacings for their purposes. We concluded that initial wide spacings with rectangularities up to 2:1, such as 6 by 3 m, result in efficient production of large trees of high value and satisfactory quality. Pruning of widely spaced trees to enhance lower bole quality is strongly recommended.

Contents

1 **Introduction**
1 **The Study**
1 The Study Area
2 The Trials
4 Sampling and Measurements
6 Fully stocked subplots
6 Subsequent Treatments
7 **Results and Discussion**
7 The 49-Tree-Plot and 0.2-ha-Plot Trials
9 Height
11 Diameter
13 Stem form
13 Crown width
16 Height to live crown and natural pruning
16 Crown length and crown ratio
19 Crown shape
19 Survival and mortality
22 Diameter frequency distribution
25 Basal area per hectare
27 Total-stem volume
27 Merchantable volume
28 The Rectangularity Trial
28 Survival and mortality
29 Height
33 Diameter
35 Stem form
37 The Nelder-Plot Trial
37 Nelder-plot 1 (pure Douglas-fir)
38 Nelder-plot 2 (four species)
41 The Variable-Block Trial
42 Other Factors to Consider
43 Relation to Targets
43 **Conclusions**
44 **Acknowledgments**
44 **English and Metric Equivalents**
45 **Literature Cited**
46 **Appendix**

Introduction

Influences of initial spacing on stand development are of considerable economic and biological importance. Much has been learned from a study of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) at the Wind River spacing trials on site IV land in southwest Washington (Reukema 1979), but foresters in the Pacific Northwest lack published data on establishment and early growth of Douglas-fir and associated species on good sites. This paper reports development of Douglas-fir, western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and western redcedar (*Thuja plicata* Donn ex D. Don) on site I land at the University of British Columbia (UBC) Research Forest near Maple Ridge (Haney), British Columbia.

The results summarized in various progress reports (Smith 1983, Walters and Smith 197 have been synthesized and further evaluated for this paper. Our information should be useful to managers interested in growing trees to meet a wide range of managerial objectives.

The Study

The Study Area

The UBC Research Forest is north of Maple Ridge, in the Fraser River Valley; latitude 49°18′ N., longitude 122°35′ W. The five trials are all within an area of less than 45 ha, and the most distantly separated plots are less than 1 km apart (fig. 1). The area is about 180 m above sea level on land that slopes gently to the southwest. The soil is a gleyed, micro-podzol with mull humus and with sandy loam to loamy sand texture. Precipitation includes an average of 2040 mm of rain and 1260 mm of snow per year, which yields an annual water equivalent of 2166 mm; summer droughts are common. Daily temperature averages about 9 °C.

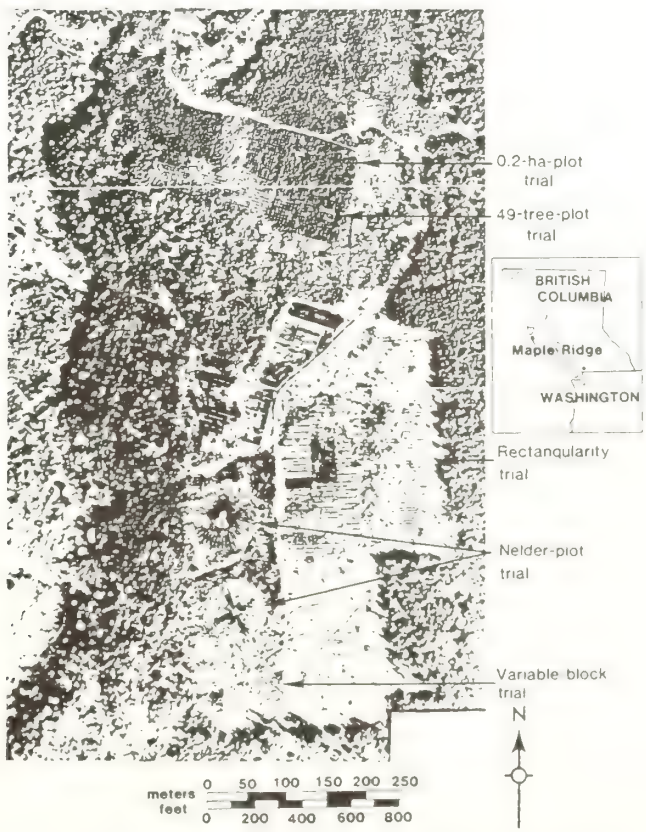


Figure 1—Relative locations of the spacing trials at the University of British Columbia Research Forest near Maple Ridge (Haney), British Columbia.

The area on which the first trials were established supported old-growth Douglas-fir, western hemlock, and western redcedar until 1955 when it was logged. The stand in that area included a few 500- to 800-year-old Douglas-fir. The apparent site indices indicated by the old-growth trees were about 61 m at 100 years for Douglas-fir and 40 m at 100 years for cedar and hemlock; the corresponding site index for Douglas-fir at breast-height age 50 is approximately 43 m. The nearby area where a second set of trials was established was logged in 1963; age of Douglas-fir in that area averaged 106 years.

The spacing trials were established soon after the areas were logged. Site preparation was done by bulldozer; large stumps were not removed from the areas logged in 1955. Logging slash was piled and burned. Some soil compaction occurred during site preparation. The site supported substantial lesser vegetation and hardwoods.

The Trials

The trials were established not only to assess effects of spacing on tree and stand development but also to determine the practicality and efficiency of different experimental designs (Smith 1959, 1978). For this report, the trials are designated (1) 49-tree-plot trial, (2) 0.2-ha-plot trial, (3) rectangularity trial, (4) Nelder-plot trial, and (5) variable-block trial. All trials are being continued.

Most trials were planted with 2+0 stock of suitable provenance that was grown nearby at the Green Timbers Nursery. The Nelder-plot and variable-block trials were planted with extra large (2+2) stock — either nursery stock or, in some cases, local wildlings that were grown in transplant beds for an additional 2 years before being outplanted.

All five trials include Douglas-fir planted in pure stands at various spacings; this facilitates comparison among the different experimental designs. The 49-tree-plot trial provides a basis for comparing relative response of Douglas-fir, western redcedar, and western hemlock to a range of spacings; this is supplemented by data from Nelder-plot 2 and the variable-block trial. The rectangularity trial provides data needed to assess responses of mixed (50:50) Douglas-fir/western hemlock stands to various spacings and spatial arrangements; it also enables a comparison with pure Douglas-fir planted at the same spacings. Sitka spruce (*Picea sitchensis* (Bong.) Carr.) was included only as a minor component of Nelder-plot 2 and the variable-block trial.

Establishment of spacings and all measurements taken through 1975 were in imperial units; the data were converted to metric units for this report. Measurements taken since 1975 have been in metric units. Reported spacings have been rounded to the nearest decimeter for ease in reading; corresponding per-hectare values were derived from the exact spacings.

A summary of these trial designs and the periods of evaluation included in this report is shown in table 1, and additional detail is given in the appendix (table 11). A brief description of each design follows.

49-tree-plot trial — The 49-tree-plot trial tests the effects of square spacings on development of three species (Douglas-fir, western redcedar, and western hemlock) grown in pure stands. Spacings are 0.9, 1.8, 2.7, 3.7, and 4.6 m (3 to 15 feet). Small plots range from 0.008 ha for the 0.9-m spacing to 0.102 ha for the 4.6-m spacing; each has two replicates (fig. 2). Seedlings that died the first year were replaced with 3+0 stock to maintain the desired stocking. Stands were cleaned and weeded several times.

Table 1—Summary of trial designs and their periods of evaluation for this report

Trial	Species 1/	Number of Spacings	Nominal growing space	Stock used	Establishment date	Most recent data: Date	Most recent data: Age 2/
			m^2/tree				
49-tree plots	DF	5	0.8-20.9	2+0	Fall 1957	Fall 1980	25
	WRC	5	.8-20.9	2+0	Fall 1958	Fall 1981	25
	WH	5	.8-20.9	1+1	Spring 1959	Fall 1981	25
0.2-ha plots	DF	5	.8-20.9	2+0	Fall 1957	Fall 1980	25
	WH	1	.8	1+1	Spring 1959	Fall 1981	25
Rectangularity	DF	9	.8-15.1	2+0	Spring 1967	Fall 1984	20
	DF+WH	9	.8-15.1	2+0	Spring 1967	Fall 1984	20
Nelder-plot 1	DF	3/ 15	.8-24.4	2+2	Fall 1965	Fall 1981	20
Nelder-plot 2	DF	3/ 15	.8-24.4	2+2	Spring 1966	Fall 1981	20
	WH	3/ 15	.8-24.4	4/ ?+2	Spring 1966	Fall 1981	20
	WRC	3/ 15	.8-24.4	4/ ?+2	Spring 1966	Fall 1981	20
	SS	3/ 15	.8-24.4	2+2	Spring 1966	Fall 1981	20
Variable-block	DF	3	.8-20.9	2+2	Spring 1966	Spring 1984	22
	WH	2	7.5-20.9	2+2	Spring 1966	Spring 1984	22
	WRC	2	.8- 3.3	4/ ?+2	Spring 1966	Spring 1984	22
	SS	1	3.3	2+2	Spring 1966	Spring 1984	22

1/ DF = Douglas-fir, WRC = western redcedar, WH = western hemlock, SS = sitka spruce.
2/ Total age of trees from seed.
3/ Continuous increase in spacing on successive arcs.
4/ ? = wildings of unknown age.

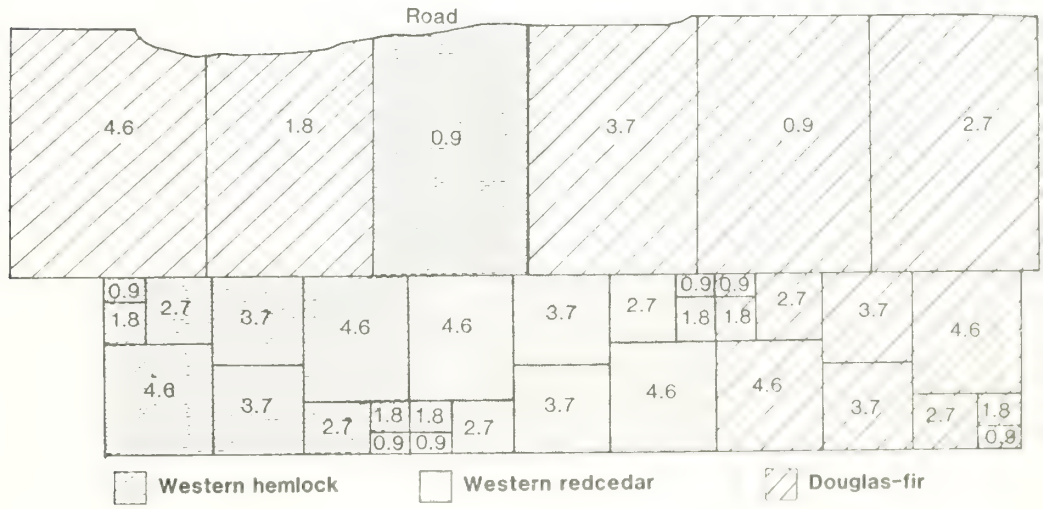


Figure 2—Layout of the 0.2-ha-plot and 49-tree-plot trials. Numbers indicate spacing between trees in meters. DF = Douglas-fir, WH = western hemlock, and WRC = western redcedar.

CLEMSON UNIVERSITY
PUBLIC DOCUMENTS DEPT.

0.2-ha-plot trial — The 0.2-ha-plot trial tests the effects of square spacings of 0.9, 1.8, 2.7, 3.7, and 4.6 m (3 to 15 feet) on development of Douglas-fir; it also includes western hemlock at the 0.9-m spacing. Large plots vary from 0.198 to 0.251 ha, plus buffers; they are not replicated (fig. 2). Seedlings that died the first year were replaced with 3+0 stock to maintain the desired stocking. Stands were cleaned and weeded several times.

Rectangularity trial — The rectangularity trial tests the effects of nine spacing arrangements, with rectangularity ranging from 1:1 to 2:1: 0.9 by 0.9, 1.4 by 1.4, 1.8 by 1.8, 2.7 by 1.8, 3.7 by 1.8, 2.7 by 2.7, 3.7 by 2.7, 4.6 by 2.7, and 5.5 by 2.7 m (3 by 3 to 18 by 9 feet). Each spacing arrangement is used for pure Douglas-fir and for alternating rows of Douglas-fir and western hemlock. Plot size generally increases with increased spacing and ranges from 0.033 ha for one plot at close spacing to 0.590 ha for plots at the widest spacing (fig. 3). Dead seedlings were not replaced. Plots were cleaned and weeded several times.

Nelder-plot trial — Nelder-plot 1 tests a continuous range of spacing of Douglas-fir along 36 spokes and constant spacing along 12 spokes that radiate from the center of the circular plot. (See Nelder (1962) for a complete discussion of the designs.) Thirty-six spokes are used for a test of spacings ranging from about 0.9 by 0.9 to 4.9 by 4.9 m (3 by 3 to 16 by 16 feet). Twelve spokes are used to test effects of rectangularity ranging from about 1:1 to 4:1, all trees having 9.3 m^2 of available growing space; that is, spacings range from about 3.0 by 3.0 to 6.1 by 1.5 m (10 by 10 to 20 by 5 feet) (fig 4). The plot was planted with large stock; dead seedlings were not replaced. The plot was cleaned and weeded several times.

Nelder-plot 2 tests a continuous range of spacings of four species along 48 spokes. The sequence of three spokes of Douglas-fir, three spokes of western hemlock, three spokes of Sitka spruce, and three spokes of western redcedar is replicated four times. All 48 spokes are used to test square spacings of 0.9 to 4.9 m. The plot was planted with large stock; dead seedlings were not replaced. The plot was cleaned and weeded several times.

Variable-block trial — The variable-block trial was established on an area with moist to wet microsite conditions. Four species were planted, in pure stands, on plots ranging from 0.032 to 0.301 ha. The species and spacings thought to be most suited to each microsite were used. Douglas-fir was planted at square spacings of 0.9, 1.8, and 4.6 m (3 to 15 feet); western redcedar at 2.7 and 4.6 m; western hemlock at 0.9 and 1.8 m; and Sitka spruce at 1.8 m. The plot was planted with large stock. There was no replanting and, prior to 1984, no cleaning or weeding.

Sampling and Measurements

Variables measured on sample trees included height, d.b.h. (diameter at breast height), stem diameters at the root collar and at 2.74 m above ground, crown width, and heights to live and dead crown; number of live trees were tallied. The per-hectare values for number of trees, basal area, and volume were computed.

Heights of Douglas-fir in the 49-tree-plot and 0.2-ha-plot trials were measured annually through age 9, and heights of hemlock in the 49-tree-plot trial were measured annually for the first 8 years. Subsequent heights in these trials and heights in other trials were measured at intervals of 1 to 7 years.

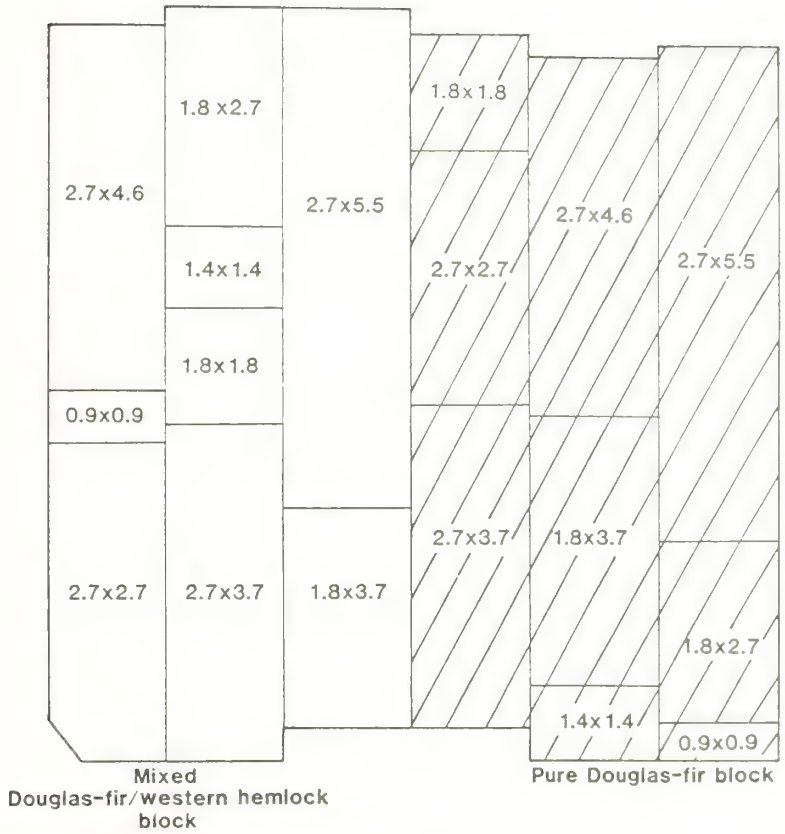


Figure 3—Layout of the rectangularity trial.

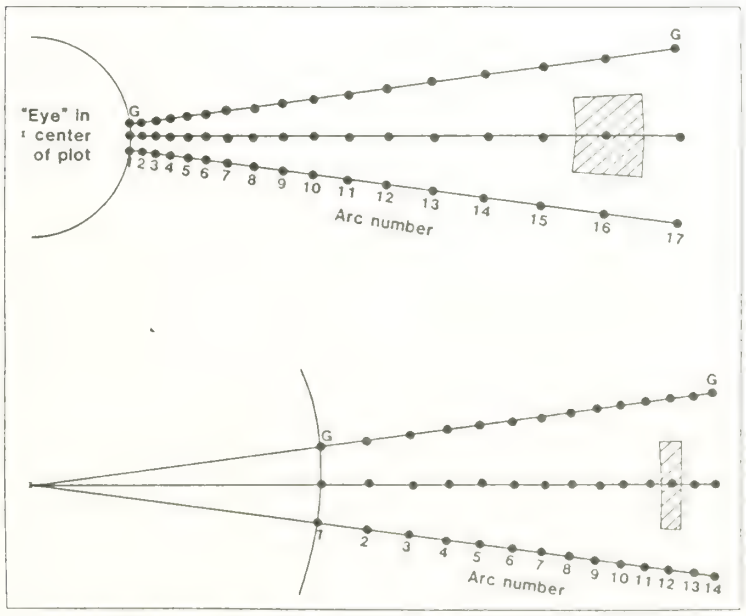


Figure 4—Spatial arrangement of trees in the Nelder-plot trial. Above: square spacings used on plots 1 and 2. Below: rectangular spacings used on one quadrant of plot 1. (Crosshatched areas show the nominal growing space available to a tree.)

In the 49-tree-plot trial, heights were measured on alternate rows of trees; the sample size ranged from 21 to 28 trees per plot, less adjustments for missing trees. On the 0.2-ha-plot and rectangularity trials, heights were measured on subsamples of various sizes; at the last measurement (age 20) on the rectangularity trial, all trees were measured for height. In the Nelder-plot-trial, all trees were measured for height each time.

Measurements of d.b.h. were begun in the 49-tree-plot trial at age 8 for Douglas-fir and at age 10 for cedar and hemlock. Trees were measured at irregular intervals thereafter, and all trees were measured each time. Measurements of d.b.h. were begun at age 13 in the 0.2-ha-plot trial, at age 10 in the rectangularity trial, and at age 11 in the Nelder-plot trial; diameter measurements were taken for all trees.

Measurements of crown width, height to live and dead crown, and diameters at root collar and at 2.74 m were made on the same trees as were measured for height in the 49-tree-plot trial, except for Douglas-fir at age 25. In other trials, and on the 49-tree Douglas-fir plots at age 25, these variables were measured only on the center trees of fully stocked subplots.

Fully stocked subplots — Initial planting gaps and subsequent mortality reduced planned density by various degrees and reduced precision of estimates of initial spacing effects. Fully stocked subplots were established to quantify effects of spacing "without error." Each fully stocked subplot consists of a square block of nine trees—a center tree surrounded by eight competitors—that represented initial full stocking. All nine trees were alive at the time the subplot was established, but some have died since. Some of the nine trees may be common to more than one subplot.

Measurements made on center trees included diameters at root collar, breast height, and 2.74 m above ground; height to base of dead and live crown; total height; and crown width. Each time the center trees were measured, the eight surrounding trees were also measured for d.b.h.

Subsequent Treatments

Subplots in the 49-tree-plot and 0.2-ha-plot trials were identified and measured in July 1974. For the 49-tree-plot trial, six subplots were established for each spacing of each species (three subplots per plot) for a total of 90 center trees. For the 0.2-ha-plot trial, six subplots were established in each of the six plots (five Douglas-fir and one hemlock) for a total of 36 center trees. These 126 center trees and their surrounding trees were remeasured after the 1976, 1980 or 1981, and 1983 growing seasons.

Fully stocked subplots were established more recently in the rectangularity and variable-block trials. The number of subplots in these trials vary irregularly, with survival, from one plot to another.

In addition to replanting, weeding, and cleaning, other "treatments" were superimposed on some plots.

Pruning — On most plots, branches were removed (brashed) to a height of about 2 m for easy access and to make the plots more suitable for demonstration purposes. In the 49-tree-plot and 0.2-ha-plot trials all surviving trees in the centers of the 126 fully stocked subplots were pruned in 1977 to a height of about 6 m; this was done to determine effects of pruning and spacing on the quality of tree bole.

Thinning — In the plots at the 0.9- by 0.9-m and 1.4- by 1.4-m spacings in the mixed Douglas-fir/hemlock block of the rectangularity trial, portions of each plot were thinned diagonally (to preserve the species mixture) in 1974: On one third of the plot, every third row of trees was cut and on another third of the plot, every second row of trees was cut. In Nelder-plot 1 (pure Douglas-fir), all trees in spokes 1-24 of arc 2 and in spokes 13-24 of arc 4 were cut in 1974: Thus, in quadrant 1, trees in arc 3 were released on one side; in quadrant 2, trees in arc 3 were released on two sides and trees in arc 5 were released on one side.

Results and Discussion

The greatest amount of information available is from the 49-tree-plot and 0.2-ha-plot trials, so our attention focuses on those trials. Trees in those two trials are the same age, and the trials are immediately adjacent. Data were available for trees up to age 25, the early mortality had been replaced, and there was information on crown development and yields per hectare. The other trials are younger, but provided supplementary information.

All five trials provided information on development of Douglas-fir. Only the 49-tree-plot trial provided substantial data on relative development of three species—Douglas-fir, western redcedar, and western hemlock. The rectangularity trial provided some information on comparative development of pure Douglas-fir and western hemlock grown in mixture. The hemlock, cedar, and spruce components of the Nelder-plot and variable-block trials are minor and provided little information.

The 49-Tree-Plot and 0.2-ha-Plot Trials

We discuss results from the 49-tree-plot and 0.2-ha-plot trials in terms of (1) bole dimensions and form—height, diameter, stem form; (2) crown size and shape—crown width, height to live crown, crown length and crown ratio, crown shape; and (3) stand development per hectare—survival and mortality, d.b.h. frequency distribution, basal area, total-stem volume, merchantable volume.

Average bole and crown dimensions for trees in the 49-tree-plot trial at age 25 are shown in table 2. For d.b.h. and height, these are the averages of all live sample trees (trees that were measured for height). The other variables reported were measured on these same sample trees for cedar and hemlock; for Douglas-fir, the other variables were estimated from regressions fitted to data from fully stocked subplots.

Relative bole and crown sizes of the three species at ages 12, 20, and 25 are shown in figure 5, which is a synthesis of observed averages for the 49-tree-plot trial. Douglas-fir has obviously grown bigger and taller than cedar and hemlock. At initial spacings of 0.9 and 1.8 m, crowns began to lift early, remained narrow and short, and supported small trees with little taper. At initial spacings of 3.7 and 4.6 m, crowns spread wide, lifted late, and supported much larger and more tapered boles.

Trends of tree and stand development over time prior to age 25 are presented graphically in figures 6-17. All trends are shown as functions of age. Some trends are also plotted as functions of attained mean height. The advantage of expressing effects of spacing on other variables as functions of height (for the time trend) is that it facilitates comparing stands planted at common spacings that grow at different rates. This facilitates comparisons among species grown in the UBC trials. It also facilitates comparisons within species for stands growing at different locations, such as Douglas-fir grown in the UBC trials vs. the Wind River trials.

Table 2—Average bole diameters, stem form, and crown dimensions of sample trees at age 25 in the 49-tree-plot trial, by species and by spacing[1]

		Diameters			Stem form		Crown dimensions					
Spacing	Height	RCD	DBH	D2.7	H/D	D2.7/DBH	CW	HLC	HDC	CL	CL/H	CL/CW
- - - Meters - - -		- - Centimeters - -					- - - - Meters - - - -					
					DOUGLAS-FIR							
0.9	20.1	17.0	14.6	14.0	138	0.96	2.7	12.2	--	7.9	0.39	2.9
	18.2	15.2	13.1	12.5	139	.95	2.5	11.6	--	6.6	.36	2.6
1.8	18.6	20.6	16.9	15.6	110	.92	2.5	11.1	--	7.5	.40	3.0
	20.9	19.3	16.2	15.0	129	.93	2.6	12.1	--	8.8	.42	3.4
2.7	20.5	26.5	21.5	19.8	95	.92	3.0	10.6	--	9.9	.48	3.3
	21.8	29.6	23.9	22.0	91	.92	3.2	10.8	--	11.0	.50	3.4
3.7	20.7	34.6	27.7	25.6	75	.92	3.8	8.9	--	11.8	.57	3.1
	22.1	31.9	25.9	23.9	85	.92	3.8	9.7	--	12.4	.56	3.3
4.6	21.3	35.9	29.3	27.2	73	.93	4.7	7.6	--	13.7	.64	2.9
	19.6	36.9	29.9	27.8	66	.93	4.6	6.8	--	12.8	.65	2.8
Average	20.4					.93						3.1
					WESTERN REDCEDAR							
0.9	12.3	16.7	10.4	9.8	119	.94	2.1	6.6	2.2	5.7	.46	2.7
	12.8	18.6	11.5	10.7	111	.93	2.6	5.0	2.1	7.8	.61	3.0
1.8	14.3	25.3	15.7	14.3	91	.91	2.8	6.4	2.3	7.9	.55	2.8
	14.3	25.8	17.2	15.2	83	.88	3.1	5.0	2.1	9.3	.65	3.0
2.7	13.6	34.5	21.0	17.5	65	.83	3.6	3.9	1.5	9.7	.71	2.7
	16.1	38.0	24.6	23.2	65	.94	4.2	3.9	1.8	12.2	.76	2.9
3.7	12.8	28.6	20.5	17.2	62	.84	4.0	2.1	.7	10.6	.83	2.6
	15.5	37.0	26.0	21.4	59	.82	4.6	2.4	0	13.1	.85	2.8
4.6	14.4	38.0	26.0	20.0	56	.77	5.5	2.1	0	12.3	.85	2.2
	15.2	31.3	27.0	22.0	56	.81	4.5	2.0	1.2	13.2	.87	2.9
Average	14.1					.86						2.8
					WESTERN HEMLOCK							
0.9	11.8	12.8	10.1	9.6	117	.95	2.4	2.5	2.1	9.3	.79	3.9
	11.5	10.8	9.2	8.5	125	.92	2.5	2.8	1.7	8.7	.76	3.5
1.8	12.3	14.9	11.8	10.9	104	.92	3.5	3.3	1.2	9.0	.73	2.6
	12.5	17.1	13.6	12.9	92	.95	3.5	2.8	1.6	9.7	.78	2.8
2.7	12.1	18.7	13.8	13.0	86	.94	4.6	2.7	1.6	9.4	.78	2.2
	12.0	20.2	15.0	14.4	80	.96	3.7	2.6	1.9	9.4	.78	2.5
3.7	13.2	19.5	17.1	16.0	77	.94	4.9	2.1	1.7	11.1	.84	2.3
	14.0	26.5	19.2	18.4	73	.96	4.5	2.3	1.6	11.7	.84	2.6
4.6	12.6	20.8	16.6	16.0	76	.96	4.4	1.8	0	10.8	.86	2.4
	12.8	23.1	17.4	16.5	73	.95	4.3	2.1	1.1	10.7	.84	2.5
Average	12.5					.94					.80	2.7

-- = not applicable.

1/ Abbreviations: RCD = root collar diameter; D2.7 = diameter at a height of 2.7 m; H/D = ratio of height to d.b.h.; CW = crown width; HLC = height to live crown; HDC = height to dead crown; and CL = crown length.

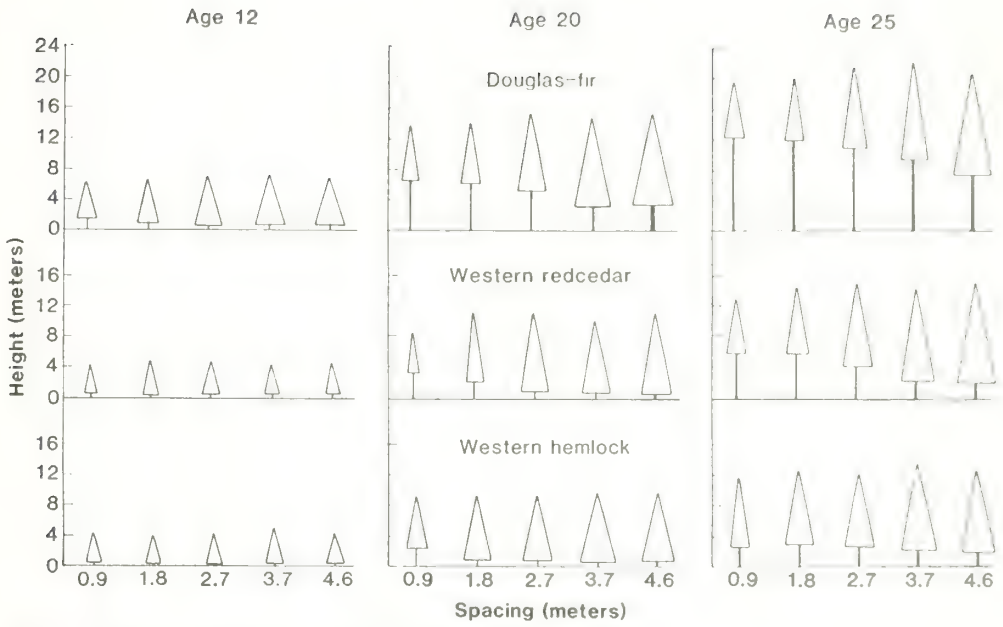


Figure 5—Relative bole and crown sizes of Douglas-fir, western redcedar, and western hemlock at ages 12, 20, and 25 in the 49-tree-plot trial.

For most variables, trends over time were consistent among species and among spacings for spacings of 1.8 to 4.6 m. Trends for the 0.9-m spacing were commonly quite irregular, mostly because of the greater mortality at this close spacing. There were differences in rates of development and, thus, in attained levels.

Generally the 0.2-ha-plot trial exhibited the same trends as the 49-tree-plot trial. The one major exception was mortality of Douglas-fir at the 0.9-m spacing, which was much greater in the larger plot (0.2-ha-plot trial), mostly because of snow press.[1]

Height — For all three species, spacing had little effect on height. The small differences among spacings in curves of both top height and mean height as functions of age are not consistently related to spacing; they include irregularities (fig. 6).

Top height — Top heights were initially a little taller at close spacings because of more opportunities for natural selection of superior genotypes and microsites; this is consistent with a phenomenon hypothesized by Mitchell and Cameron (1985). These initial natural selection advantages for the many trees planted at close spacings disappeared, however, as height growth of dominant trees was repressed by intense competition for growing space. Trends of Douglas-fir top heights over time closely followed Bruce's (1981) curve for site index 45 m at breast-height age 50. Apparent trends in top height were irregular, and there was no clear effect of spacing on current top height for any of the three species. Data suggest that top heights at age 25 might have been greatest at intermediate spacings; and recent growth tended to be least at the closest spacing. Whether or not future height growth will be substantially favored by initial wide spacings, as at Wind River (Reukema 1979), remains to be seen.

[1]Snow press means that snow pressed tree crowns out of the canopy and contributed to the eventual fall to the ground of the tree, individually and in clumps.

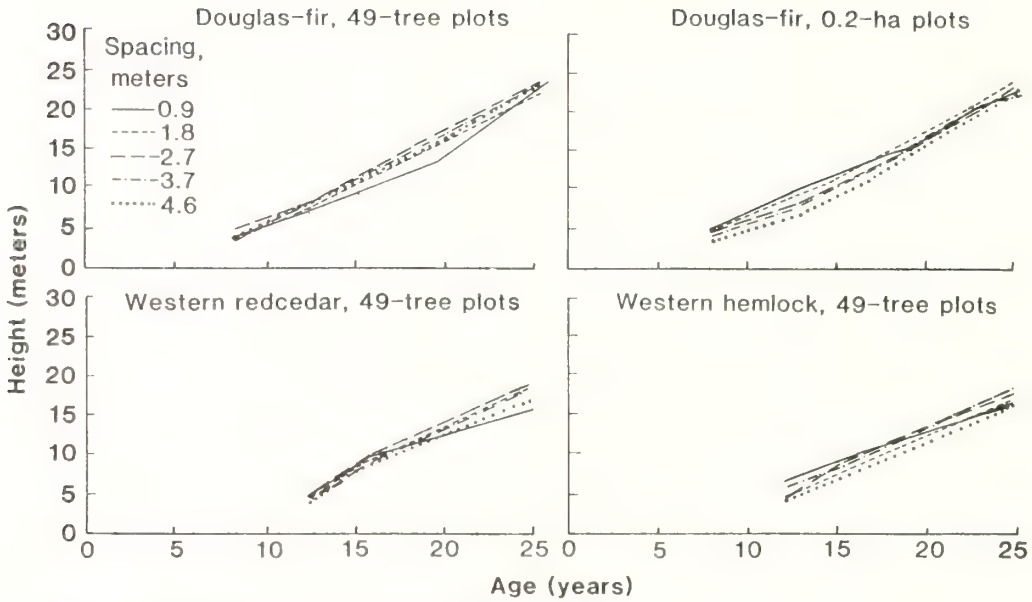


Figure 6a—Top height (100 largest trees per hectare), by age and by spacing, of Douglas-fir in the 49-tree-plot and 0.2-ha-plot trials and of western redcedar and western hemlock in the 49-tree-plot trial.

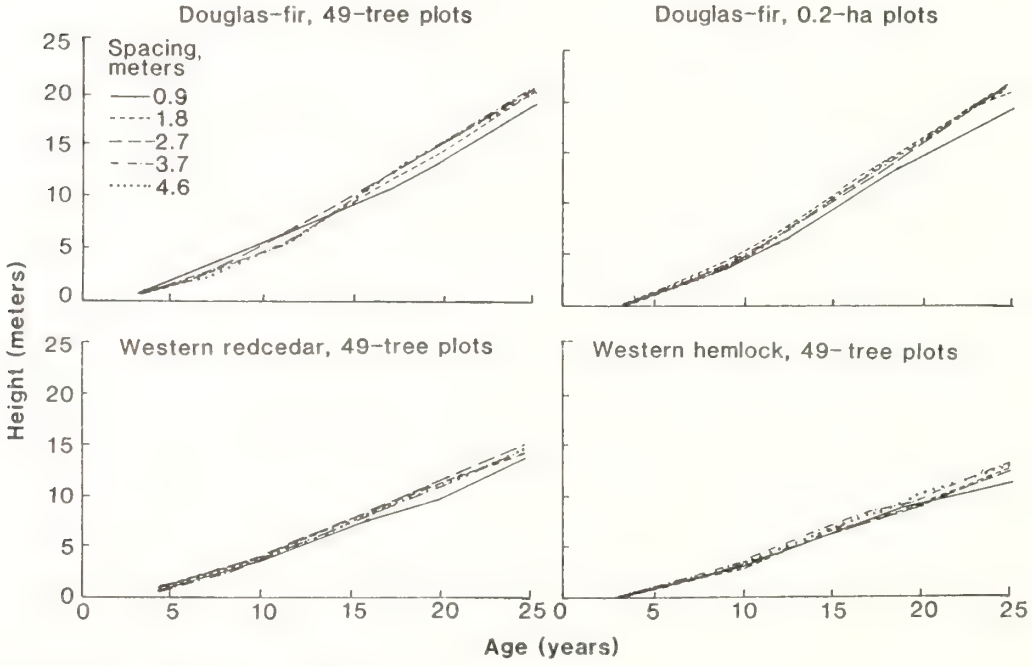


Figure 6b—Mean height, by age and by spacing, of Douglas-fir in the 49-tree-plot and 0.2-ha-plot trials and of western redcedar and western hemlock in the 49-tree-plot trial.

Mean height — Relative to top heights, mean heights generally increased with increased spacing. At age 25, the difference between top height and mean height of Douglas-fir on the 0.2-ha-plot trial ranged from about 3.8 m at the 0.9-m spacing to 0.8 m at the 3.7-m spacing. The mean height curves in recent years were consistently lowest for the 0.9-m spacing. The curves for the 0.9-m spacing usually reached this lowest position by abrupt shifts in position, which might be associated with breakage or might reflect sampling and measurement errors.

For Douglas-fir in the 49-tree-plot trial, mean heights at age 25 averaged 20.4 m; the average for the 0.9-m spacing was about 6 percent shorter. There is no clear indication that differences are becoming greater. Trends of apparent height growth in the 0.2-ha-plot trial were more irregular, but differences generally showed no consistent relation to spacing; average height at the 0.9-m spacing was a little shorter than heights at the wider spacings. Heights at age 26 averaged 20.2 m; the average for the 0.9-m spacing was about 7 percent shorter.

For western redcedar, the greatest separation of curves apparently occurred between ages 16 and 20. Heights at age 25 averaged 14.1 m; the average for the 0.9-m spacing was about 11 percent shorter. For western hemlock, trees were tallest at the 3.7-m spacing. At age 25, average height for all spacings was 12.5 m; the average for the 0.9-m spacing was 6 percent shorter and that for the 3.7-m spacing was 9 percent taller.

Diameter — Average d.b.h. of all three species was strongly influenced by spacing (fig. 7). Curves of diameter as a function of age are generally quite consistent, despite some minor irregularities. The curve for the 0.9-m spacing is always the lowest (smallest diameters), and elevation of curves generally increases with increased spacing. There was some crossing of curves in the past because of differences in early growth rates that were associated with factors other than spacing.

Apparent differences between the 49-tree-plot and the 0.2-ha-plot trials in recent trends over time (diameter has leveled off in the 0.2-ha-plot trial but not in the 49-tree-plot trial) are partly associated with differences in the amount of time between measurements; this is not the complete explanation, however. Other irregularities in elevation of curves for specific species are probably also associated with site differences.

For Douglas-fir in the 49-tree-plot trial, differences among all spacings widened over time. By age 25, quadratic mean d.b.h. (Dg) was 2.14 times as large at the 4.6-m spacing as at the 0.9-m spacing. Average diameters in the 0.2-ha-plot trial at age 13 (the first measurement) were virtually the same at all except the 0.9-m spacing. Thereafter, differences among the 1.8- through 4.6-m spacings steadily widened. By age 25, Dg was 2.19 times as large at the 4.6-m spacing as at the 0.9-m spacing. Growth at the 2.7-m spacing was a little poorer in the 0.2-ha-plot trial than in the 49-tree-plot trial, relative to that at wider spacings.

For western redcedar, differences among the three widest spacings were slight, but there was a lot of variation among plots at the same spacing (table 2). Trees at the 0.9-m spacing grew more slowly than others since age 10, whereas growth at the 1.8-m spacing did not slow down until about age 15. At age 25, Dg was 2.41 times as large at the 4.6-m spacing as at the 0.9-m spacing.

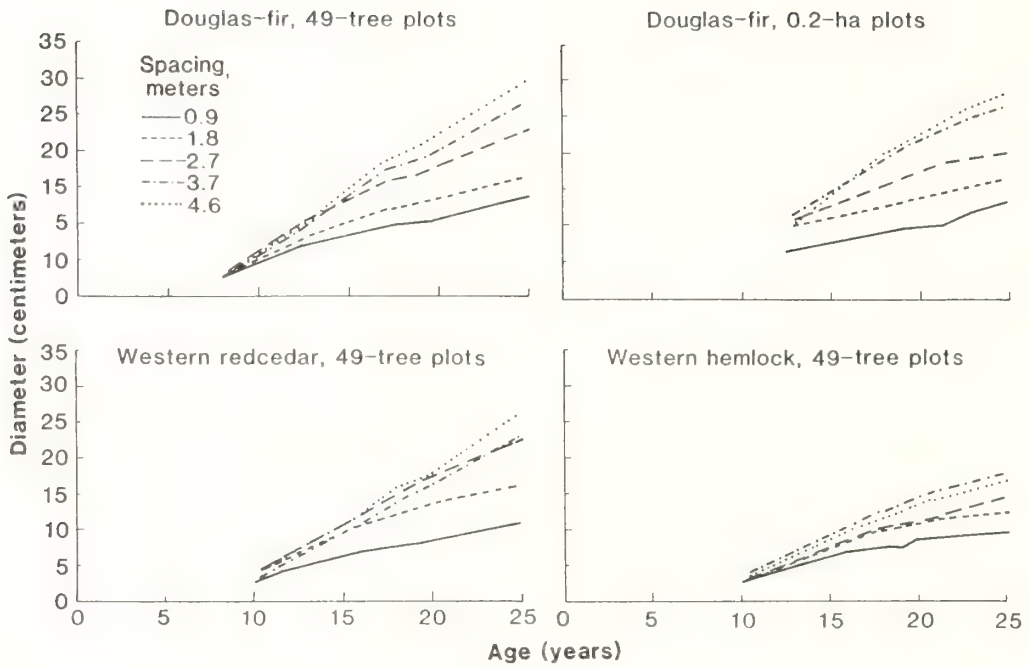


Figure 7a—Average d.b.h., by age and by spacing, of Douglas-fir in the 49-tree-plot and 0.2-ha-plot trials and of western redcedar and western hemlock in the 49-tree-plot trial.

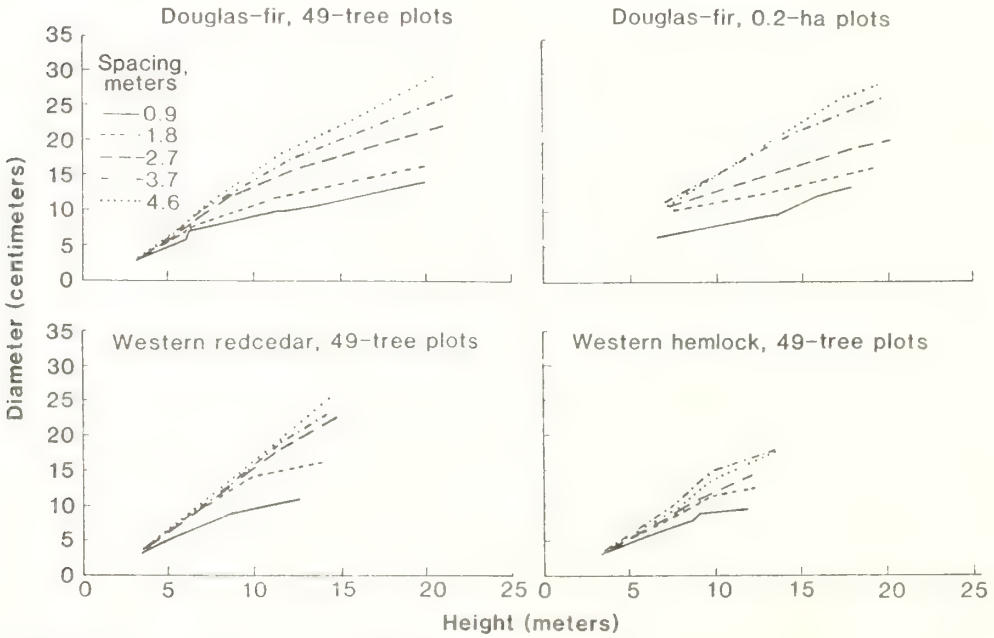


Figure 7b—Average d.b.h., by attained mean height and by spacing, of Douglas-fir in the 49-tree-plot and 0.2-ha-plot trials and of western redcedar and western hemlock in the 49-tree-plot trial.

For western hemlock, there was much less difference among spacings. Clearly the trees at the 0.9-m spacing grew the least and those at the 3.7-m and 4.6-m spacings grew the most. Growth continued to slow down at the 0.9-m and 1.8-m spacings. At age 25, Dg was 1.88 times as large at the 3.7-m spacing as at the 0.9-m spacing.

At a common average tree height of 12 m, the ranges in d.b.h. for Douglas-fir (age 17-18), western redcedar (age 22-25), and western hemlock (age 23-25) were similar (fig. 7b). Trends over time (attained height) may differ among the three species, but irregularities make it impossible to attach any degree of certainty to apparent trends and differences therein. The graphs of d.b.h. as a function of height suggest that as long as trees are open grown, this relation is nearly linear; as each stand at successively wider spacing closes, the curve breaks away quite sharply. This pattern is illustrated most clearly for western redcedar.

Stem form — Stem taper is important to both tree quality and resistance of tree stems to breakage by wind or snow. Tall, slender trees are more likely to be broken. Europeans sometimes suggest that the ratio of height to d.b.h. (H-to-D ratio) of the 100 largest trees per ha, where height and d.b.h. are expressed in the same units, should be kept to less than about 80; the ratio for the average tree might then be up to about 100 (van Tuyll and Kramer 1981).

For all three species, H-to-D ratios at age 25 in the UBC trials were strongly influenced by spacing. At the 0.9-m spacing, trees were slender; average ratios ranged from 115 for cedar to 138 for Douglas-fir. At the 4.6-m spacing, tree boles tapered strongly; average ratios ranged from 56 for cedar to 75 for hemlock (table 2).

The H-to-D ratio apparently initially declined with increasing age (to about age 10-15) for all three species. Thereafter, for Douglas-fir the ratio leveled off at the two widest spacings, but increased at other spacings—more so at closer spacings. For cedar and hemlock, the ratio continued to decline at all except the closest spacing, but then increased between ages 20 and 25 at the 0.9- and 1.8-m spacings (fig. 8). We expect H-to-D ratios to continue to increase, as was also observed by van Tuyll and Kramer (1981).

Taper of the lower bole at age 25, as measured by the ratio of diameter at 2.7 m to d.b.h. apparently was nearly independent of spacing for Douglas-fir and for western hemlock (table 2). The ratio for redcedar was more irregular, but tended to decline with increased spacing; that is, taper increased with increased spacing because of butt swell.

Crown width — Generally, the wider the spacing, the wider the crown. Crown widths initially increased with increasing age (as tree size increased). This was followed by maintenance of a nearly constant crown width for Douglas-fir and hemlock; but crown widths of cedar apparently were still increasing at wide spacings at age 25 (fig. 9).

The curves for crown width have many irregularities that cannot be readily explained (fig. 9, a and b). Decreases could be real, but may not be; most irregularities are probably associated with sampling and measurement errors. Trends were not yet clearly established by age 25. Relative to height, instead of age, some irregularities are exaggerated.

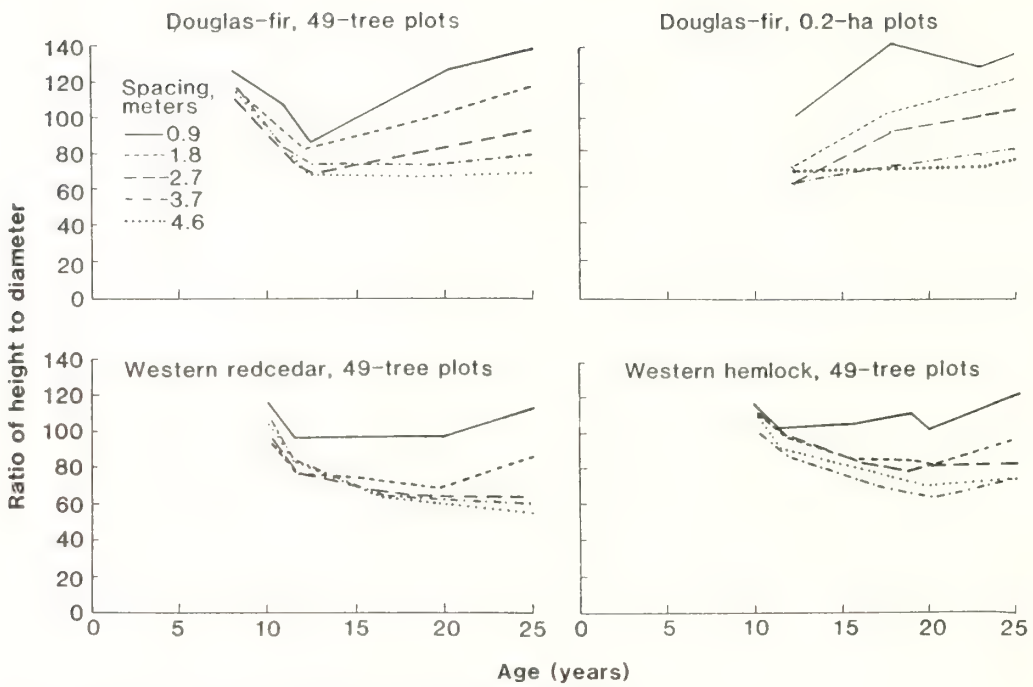


Figure 8—Ratio of height to d.b.h. (H-to-D ratio) for trees of average height and d.b.h., by age and by spacing, of Douglas-fir in the 49-tree-plot and 0.2-ha-plot trials and of western redcedar and western hemlock in the 49-tree-plot trial.

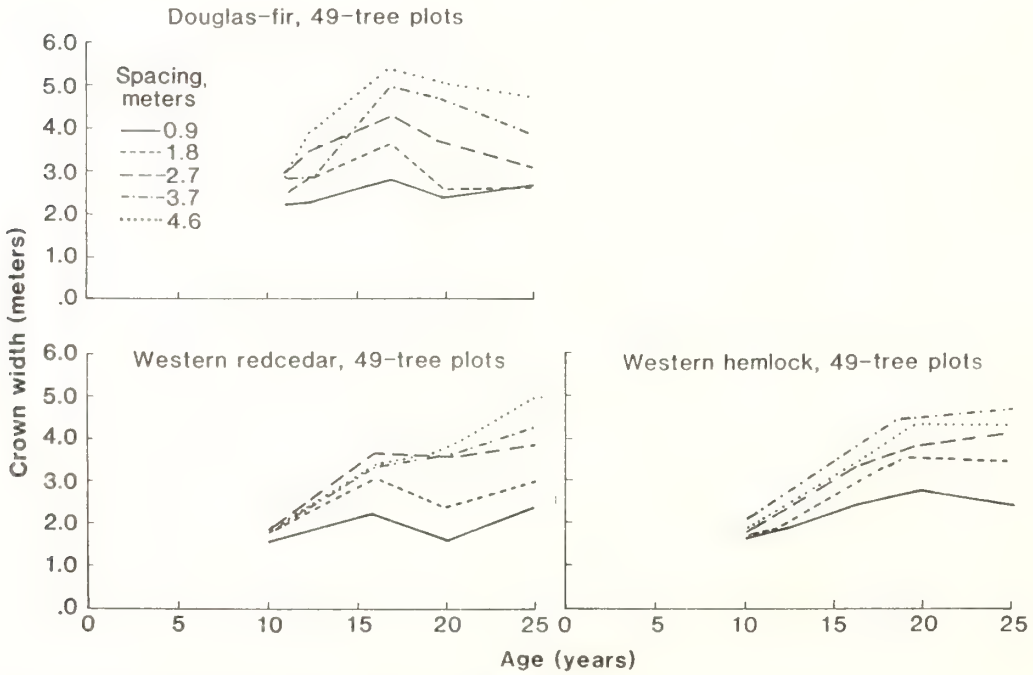


Figure 9a—Average crown width, by age and by spacing, for Douglas-fir, western redcedar, and western hemlock in the 49-tree-plot trial.

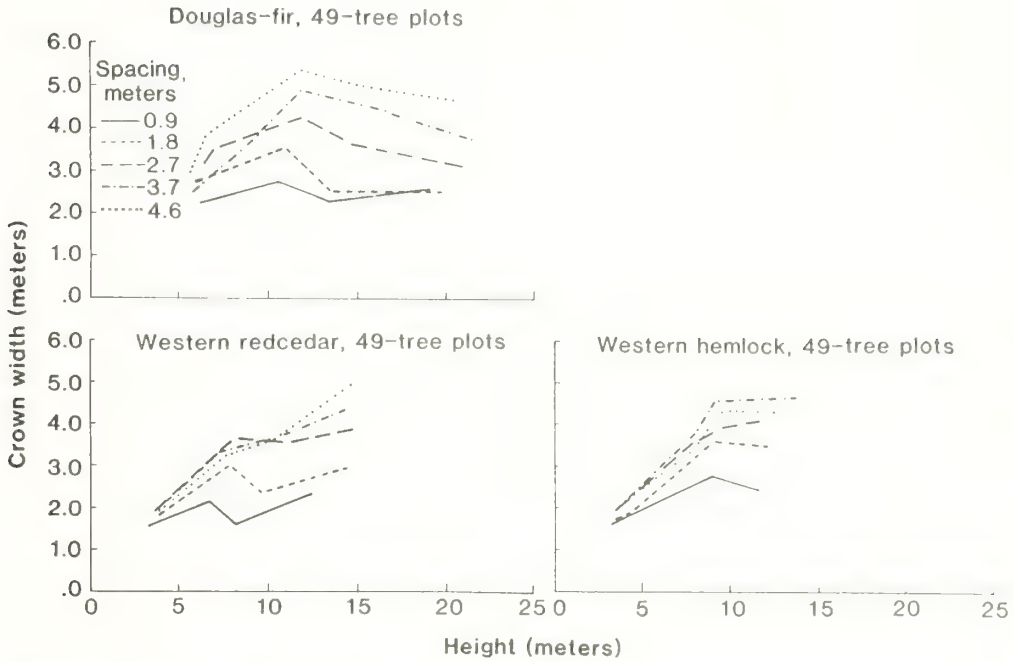


Figure 9b—Average crown width, by attained mean height and by spacing, for Douglas-fir, western redcedar, and western hemlock in the 49-tree-plot trial.

For all three species, the apparent maximum attained average crown width was consistently related to spacing:

Plantation spacing	Crown width, by species		
	Douglas-fir	Cedar	Hemlock
(m)	(m)	(m)	(m)
0.91	2.75	2.25	2.76
1.83	3.58	3.02	3.62
2.74	4.25	3.90	4.15
3.66	4.90	4.30	4.70
4.57	5.38	5.00	4.39

At the closer spacings, this maximum average crown width was much greater than the average distance between trees—a result of crown overlap. The ratio of maximum crown width to spacing declined with increased spacing in a curvilinear relationship. At the 0.9-m spacing, the maximum crown width of Douglas-fir and western hemlock was about three times the average spacing; at the 4.6-m spacing, the maximum average crown width of Douglas-fir was about 1.2 times the average spacing.

For Douglas-fir, this maximum crown width was apparently reached at about age 17 at all spacings, but the apparent difference between ages 17 and 20 may be a result of sampling error. The recent apparent increase in crown width at 0.9-m spacing could be associated with mortality of neighboring trees. For western redcedar, crown widths apparently were still increasing at age 25—at least at the two widest spacings. Crown widths differentiated by spacing in a manner similar to that for d.b.h. The indicated fluctuations possibly were "shrinkages" associated with rapid lifting of crowns. For western hemlock, this maximum crown width was apparently reached at about age 20 at all spacings.

Height to live crown and natural pruning — Height to live crown generally followed a consistent pattern. Crowns began to lift later with progressively wider spacing; once crowns began to lift, the rate of lift was similar at all spacings (fig. 10). Crowns lifted substantially on Douglas-fir, but very little on hemlock; cedar was intermediate. For Douglas-fir, the first log (6 m) was generally free of live branches at all spacings by age 25. For cedar, crowns lifted to 6 m only at the two closest spacings. Hemlock crowns barely started to lift.

At a common average tree height of about 12 m, the height to live crown at the 0.9-m spacing was just a little less for cedar than for Douglas-fir; it was much less for hemlock (fig. 10b). Heights to live crown at the three wider spacings, however, were much less for cedar than for Douglas-fir; cedar and hemlock were similar.

Douglas-fir crowns started to lift prior to age 12 and continued to lift quite rapidly. Among the three closest spacings, differences did not change much since age 12; that is, crowns at those spacings all lifted about 6 m between ages 12 and 25. At age 25, height to live crown averaged 4.7 m higher at the 0.9-m spacing than at the 4.7-m spacing. Western redcedar crowns at the 0.9-m spacing began to lift rapidly after age 16. Generally, the wider the spacing, the later and more slowly the crowns lifted. By age 25, average height to live crown was 3.8 m higher at the 0.9-m spacing than at 4.6-m spacing. For western hemlock, crowns at the 1.8-m to 4.6-m spacings lifted very little prior to age 20; between ages 20 and 25, they lifted a little more rapidly.

Natural pruning of Douglas-fir was slow and not greatly aided by close spacing because of the persistence of dead branches. Branches were not excessively large even at wide spacings; average diameter of branches at breast height increased from 1 to 3 cm over the range of spacings from 0.9 to 4.6 m. Dead branches persisted even at close spacings. Slower bole growth at close spacings reduced the advantage from somewhat more rapid self-pruning.

Crown length and crown ratio — Trends of crown length over time, derived as the difference between average tree height and average height to live crown, showed similarities but also substantial differences among the three species (fig. 11).

For Douglas-fir, crown length increased rapidly prior to age 20, with the rate of increase greater at wide spacings than at close spacings. Between ages 20 and 25, crown length apparently continued to increase at the 4.6-m spacing but tended to stabilize at all other spacings. Crown lengths at age 25 averaged 6 m (83 percent) longer at the 4.6-m spacing than at the 0.9-m spacing.

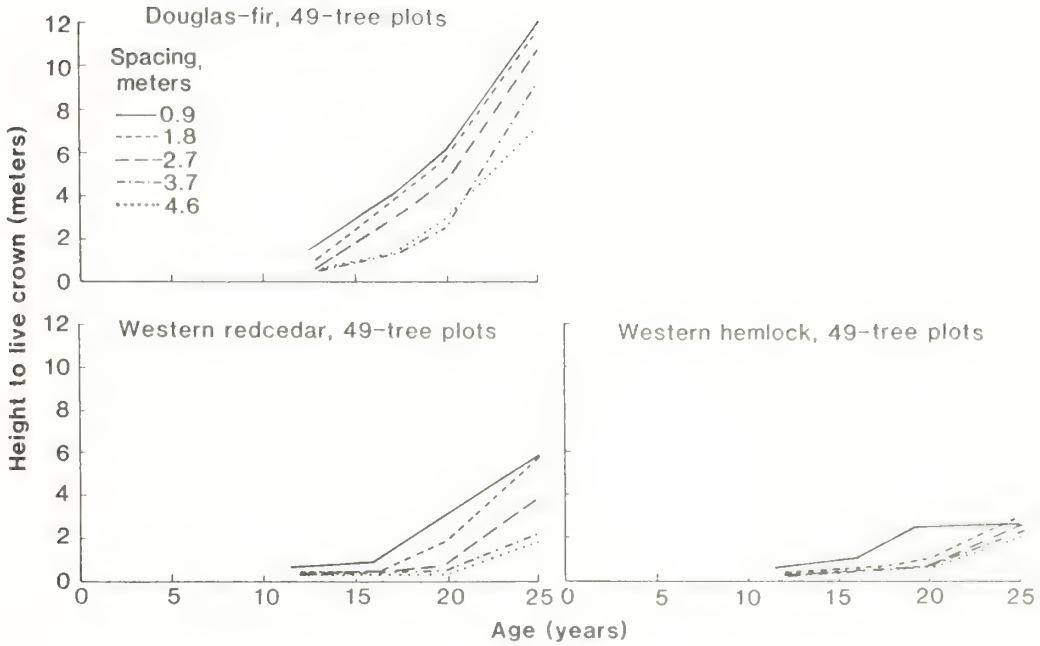


Figure 10a—Average height to live crown, by age and by spacing, for Douglas-fir, western redcedar, and western hemlock in the 49-tree-plot trial.

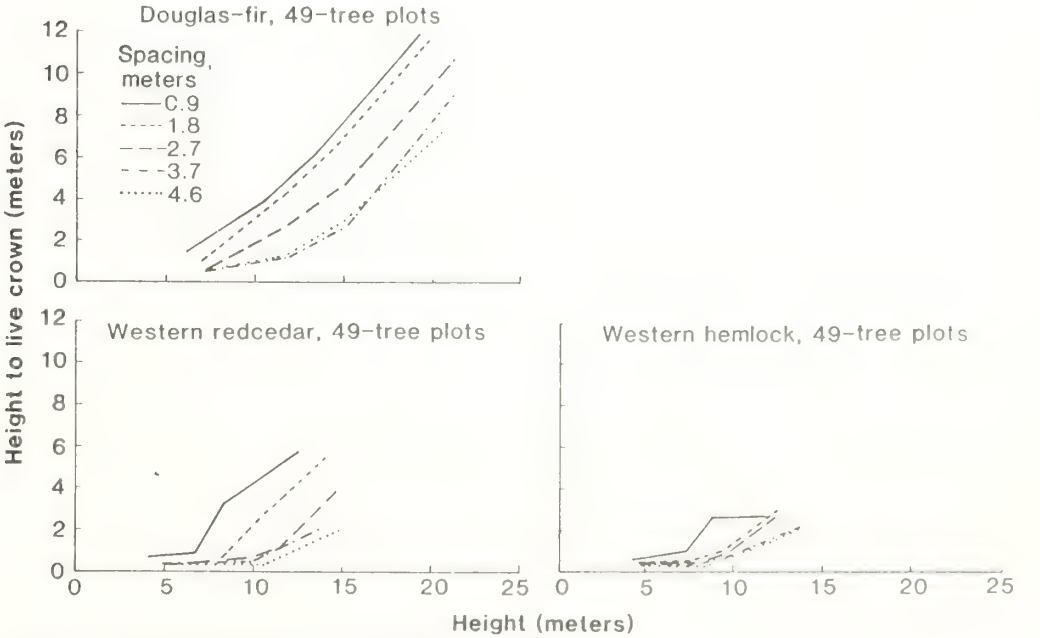


Figure 10b—Average height to live crown, by attained mean height and by spacing, for Douglas-fir, western redcedar, and western hemlock in the 49-tree-plot trial.

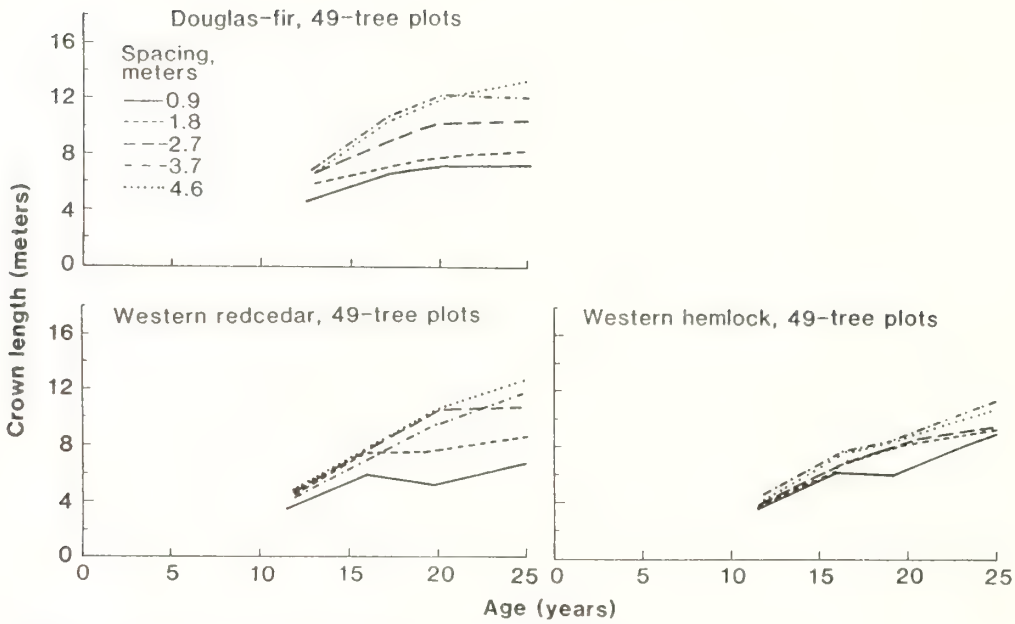


Figure 11—Crown length (derived as the difference between the average tree height and the average height to live crown), by age and by spacing, for Douglas-fir, western redcedar, and western hemlock in the 49-tree-plot trial.

For western redcedar, crown length continued to increase to age 25 at the 3.7- and 4.6-m spacings, but the rate of increase slowed down sharply after age 20 at the 2.7-m spacing and after age 16 at the 0.9- and 1.8-m spacings. Crown lengths at 25 averaged 6 m (88 percent) longer at the 4.6-m spacing than at the 0.9-m spacing.

For western hemlock, the rate of increase in crown length began slowing between ages 16 and 20, but crown lengths still increased substantially to age 25 at all spacings. Crowns were shorter at the 4.6-m spacing than at the 3.7-m spacing, which is consistent with other crown and stem dimensions. Hemlock exhibited much less range in crown length with spacing than did Douglas-fir and cedar.

At an average tree height of 12 m, the effect of spacing on crown length was least on hemlock (9.0 to 10.6 m) and greatest on cedar (6.5 to 11.5 m).

For both Douglas-fir and western redcedar, spacing had a substantial effect on the ratio of crown length to total height (crown ratio). For Douglas-fir at age 25, the average crown ratio ranged from about 38 percent at the 0.9-m spacing to 65 percent at the 4.6-m spacing (table 2). For western redcedar, it ranged from 54 (± 8) percent at the 0.9-m spacing to 86 percent at the 4.6-m spacing. For western hemlock, on the other hand, spacing apparently had very little effect on crown ratio. With the questionable exception of one plot at the 0.9-m spacing, the ratio at age 25 ranged from 73 to 86 percent.

Crown Shape — Some modelers have used crown shape, defined as the ratio of crown length to crown width (CL-to-CW ratio), as a way to estimate effects of spacing on crown development. Maguire (1984) used ratios of 1.9 for Douglas-fir and 2.2 for western hemlock. Two assumptions are that (1) crown shape is a constant for the species and (2) crown width is limited by spacing, such that lower branches do not continue to elongate once adjacent crowns touch. In reality, however, there is considerable intermingling of crowns, and definitions of both crown width and height to live crown may vary.

The CL-to-CW ratios in the UBC trials at age 25 averaged 3.1 for Douglas-fir and 2.7 for hemlock (table 2). The ratios appeared to be nearly independent of spacing for all three species. For Douglas-fir the ratio was slightly curvilinear with a peak at about the 2.7-m spacing, and for hemlock it appeared to be slightly greater at close spacings.

Survival and mortality — Trends in number of trees per hectare were consistent over time (fig. 12). Trends for the four wider spacings are more easily seen in terms of survival percentages (fig. 12b). The differences, among species and plots, in survival at the 0.9-m spacing account for most irregularities in the basal area and volume curves that are presented later.

Two aspects of mortality, in terms of number of trees lost, should be considered separately: (1) missing trees associated with planting failures—all losses prior to about age 10+, and (2) mortality that occurred subsequently—as competition started to become important at the closer spacings. We refer to these as "**pre**establishment" and "**post**establishment" mortality. **All** preestablishment mortality was caused by factors unrelated to spacing; some preestablishment mortality represents unplantable spots (because of large stumps) rather than loss of planted seedlings. Some of the postestablishment mortality was also caused by factors unrelated to spacing, as opposed to self-thinning that was related to spacing, but causes cannot be separated.

Preestablishment mortality — Even after fill planting, losses of Douglas-fir prior to age 10 averaged nearly 10 percent in both the 49-tree-plot and the 0.2-ha-plot trials and varied irregularly with spacing. In the 49-tree-plot trial, losses varied from 5 percent at the 0.9-m spacing to 14 percent at the 1.8-m spacing. In the 0.2-ha-plot trial, losses to age 13 (excluding the 0.9-m spacing) varied from 5 percent at the 1.8-m spacing to 11 percent at the 3.7-m spacing; losses at the 0.9-m spacing were 5 percent at age 5.

Losses of western redcedar at age 5 averaged 10 percent and varied irregularly from 4 percent at the 0.9- and 4.6-m spacings to 17 percent at the 2.7-m spacing. Only at the 0.9-m spacing were any trees lost between ages 5 and 16.

Losses of western hemlock at age 5 averaged 13 percent and varied irregularly from 4 percent at the 2.7-m spacing to 23 percent at the 4.6-m spacing. Losses between ages 5 and 16 were the most irregular and varied from 0 at the 0.9- and 4.6-m spacings to 6 percent at the 1.8-m spacing. Thus, total losses to age 16 averaged 16 percent and varied irregularly from 8 percent at the 2.7-m spacing to **26** percent at the 1.8-m spacing. All losses before age 16 were undoubtedly related to conditions existing at the time of planting rather than to spacing.

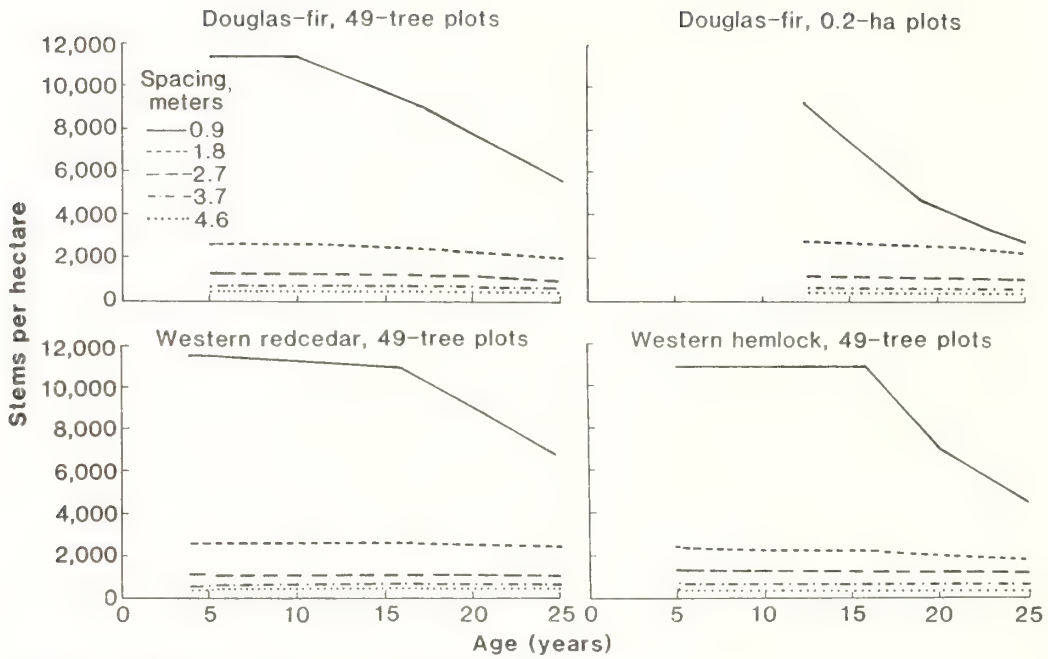


Figure 12a—Number of surviving trees per hectare, by age and by spacing, of Douglas-fir in the 49-tree-plot and 0.2-ha-plot trials and of western redcedar and western hemlock in the 49-tree-plot trial.

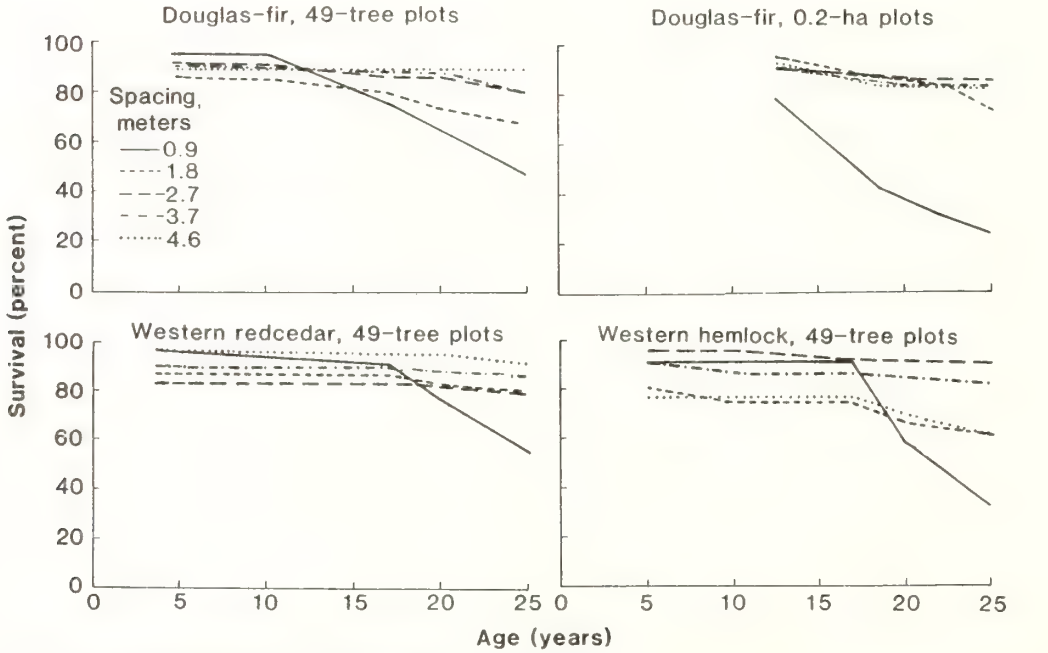


Figure 12b—Surviving trees as a percentage of the nominal number planted, by age and by spacing, of Douglas-fir in the 49-tree-plot and 0.2-ha-plot trials and of western redcedar and western hemlock in the 49-tree-plot trial.

Postestablishment mortality — Substantial losses occurred at the 0.9-m spacing for all three species. Undoubtedly, these losses were mostly associated with intense competition and abnormal stand density. Substantial mortality at the 0.9-m spacing began later for both cedar and hemlock than for Douglas-fir; mortality apparently began when average tree height was about 5 m for Douglas-fir, 6 m for cedar, and 8 m for hemlock.

For all three species, and for both the 49-tree-plot and the 0.2-ha-plot trials for Douglas-fir, mortality after the stand became established was much greater at the 0.9-m spacing than at other spacings. Furthermore, Douglas-fir losses at the 0.9-m spacing were much greater in the 0.2-ha-plot trial than on the small plots in the 49-tree-plot trial because of snow press (fig. 12). By age 25, the 0.9-m spacing had lost about 43 percent more trees per ha in the 0.2-ha-plot trial than in the 49-tree-plot trial—76 vs. 53 percent of the theoretical number planted.

Losses at other spacings (1.8 to 3.6 m) were erratically distributed by spacing and mostly were not related to spacing; the losses tended to be a little greater at 1.8-m spacing, however. Recent Douglas-fir mortality was substantial at the 1.8-m spacing in both the 49-tree-plot and the 0.2-ha-plot trials. Losses between ages 10 and 25 in the 49-tree-plot trial were 20 percent at the 1.8-m spacing, 12 percent at the 2.7-m spacing, 11 percent at the 3.7-m spacing, and none at the 4.6-m spacing. Corresponding losses between ages 13 and 25 in the 0.2-ha-plot trial were 22, 5, 7, and 12 percent. Some of these losses were due to root rot.

Most self-thinning mortality occurred in suppressed and intermediate crown classes. Causes of mortality other than those related to level of competition (self-thinning and snow press) included damage by lesser vegetation and hardwoods, root rot, spots of heavily compacted soil, damage by squirrels (hemlock), deer browsing (cedar), and bud weevil (spruce).

Western redcedar mortality between ages 16 and 25 was light, even at the 1.8-m spacing: 7 percent at the 1.8-m spacing, 5 percent at the 2.7-m spacing, 3 percent at the 3.7-m spacing, and 4 percent at the 4.6-m spacing.

Western hemlock losses during this same period were 16 percent at the 1.8-m spacing, 1 percent at the 2.7-m spacing, 5 percent at the 3.7-m spacing, and 20 percent at the 4.6-m spacing. The substantial loss at the 1.8-m spacing may have been due mostly to competition. The heavy losses at the 4.6-m spacing, however, were due to other causes: One of the hemlock plots at the 4.6-m spacing is much drier and the other is much wetter than average; both mortality and growth rate were affected. Also, some of the hemlock mortality was associated with damage by squirrels.

Table 3—Average d.b.h. and basal area per hectare of the total stand and of the 500, 250, and 100 largest trees per hectare at age 25, by spacing, for Douglas-fir in the 0.2-ha-plot and 49-tree-plot trials and for western redcedar and western hemlock in the the 49-tree-plot trial[1]

Spacing	Number of surviving trees per hectare	Height 2/	Average d.b.h. of stand component				Basal Area of stand component			
			Total stand	500 largest	250 largest	100 largest	Total stand	500 largest	250 largest	100 largest
Meters		Meters	Centimeters				Square meters per hectare			
			DOUGLAS-FIR, 0.2-HA-PLOT TRIAL							
0.9	2,898	17.8	13.4	20.1	22.0	24.5	40.8	15.8	9.5	4.7
1.8	2,213	19.5	16.7	23.0	24.9	26.9	48.7	20.7	12.2	5.7
2.7	1,128	20.2	20.6	24.7	26.8	29.2	37.5	24.0	14.1	6.7
3.7	619	19.9	27.0	28.6	31.4	34.4	35.4	32.1	19.4	9.3
4.6	392	19.4	29.4	—	32.6	35.8	26.6	--	20.9	10.1
			DOUGLAS-FIR, 49-TREE-PLOT TRIAL							
.9	5,614	19.2	13.3	20.3	21.0	21.4	78.0	16.2	8.7	3.6
1.8	2,044	19.8	16.7	22.5	24.2	26.5	44.7	19.8	11.5	5.5
2.7	1,057	21.2	22.1	26.7	28.7	31.1	40.6	28.0	16.2	7.6
3.7	595	21.4	26.3	27.7	30.9	32.7	32.3	30.1	18.8	8.4
4.6	424	20.4	28.3	--	32.2	36.6	26.7	--	20.3	10.5
			WESTERN REDCEDAR, 49-TREE-PLOT TRIAL							
.9	6,651	12.6	10.7	20.0	22.6	26.0	59.3	15.8	10.0	5.3
1.8	2,409	14.3	17.0	22.2	23.9	26.2	54.5	19.4	11.2	5.4
2.7	1,044	14.8	23.6	29.2	32.1	35.1	45.9	33.5	20.2	9.7
3.7	648	14.2	24.1	26.5	30.4	33.7	29.5	27.6	18.1	8.9
4.6	441	14.8	27.9	--	32.4	36.1	26.9	--	20.6	10.2
			WESTERN HEMLOCK, 49-TREE-PLOT TRIAL							
.9	4,576	11.6	9.7	15.6	16.3	17.1	33.8	9.5	5.2	2.3
1.8	1,860	12.4	13.1	18.5	20.7	22.8	25.2	13.5	8.4	4.1
2.7	1,207	12.0	15.3	18.9	21.3	23.7	22.1	14.0	8.9	4.4
3.7	618	13.6	18.4	20.2	22.7	25.0	16.4	16.1	10.1	4.9
4.6	293	12.7	17.6	—	18.7	22.8	7.1	--	6.9	4.1

-- = not applicable.
1/ Via d.b.h.-distribution curves; average of 2 plots for the 49-tree plots.
2/ Average height of sample trees.

Diameter frequency distribution — All components of the stand benefited, in general, from increased spacing. This can be seen in the average d.b.h. of fixed numbers of largest trees (for example, the 250 largest per ha) (table 3) and in the percentage distribution of trees by d.b.h. class (for example, the largest 20 percent of the trees) (fig. 13). Complete diameter (d.b.h.) distributions, in number per hectare by 5-cm classes, are shown in table 4.

Table 3 indicates a strong increase in mean d.b.h. for all components of the largest trees over the full range of spacings from 0.9 to 4.6 m. For Douglas-fir there is a nice progression with spacing. Western redcedar falls in two groups, with the smaller trees in the 0.9- and 1.8-m spacings and the larger trees in the other spacings. Excepting the 4.6-m plots, which are on poorer sites, mean d.b.h. of the largest hemlock increases with spacing similarly to Douglas-fir. These data make it appear quite implausible that improved opportunities for selection, associated with close initial spacing, could compensate for the reduced growth that results from overcrowding in closely spaced stands.

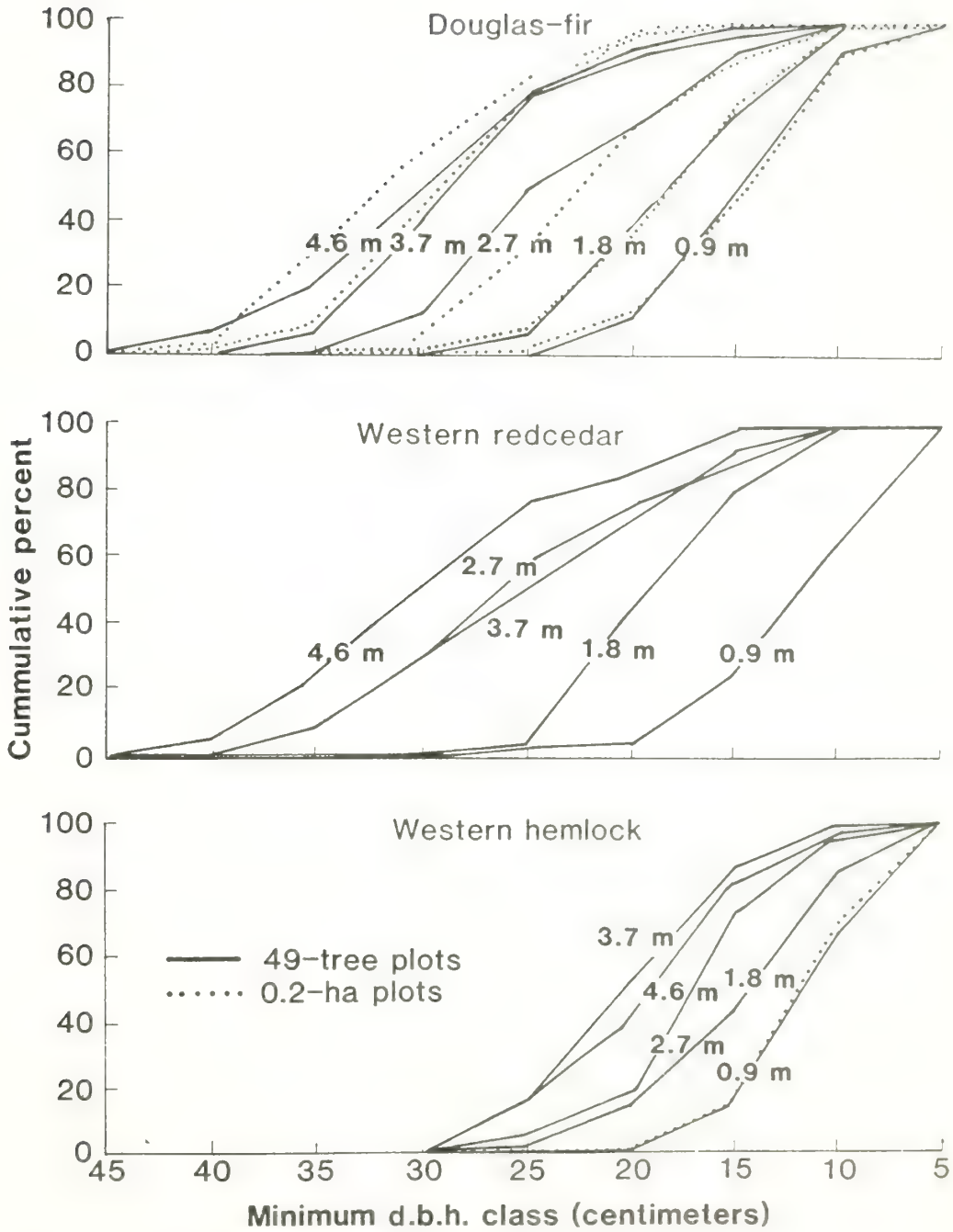


Figure 13—Distribution by percentage of trees at age 25, by minimum d.b.h. and by spacing, for Douglas-fir, western redcedar, and western hemlock.

Table 4—D.b.h. frequency distributions (number of trees per hectare) at age 25, by spacing, species, and d.b.h. class, for the 49-tree-plot and 0.2-ha-plot trials[1]

	Spacing and trial									
	0.9-m spacing		1.8-m spacing		2.7-m spacing		3.7-m spacing		4.6 m spacing	
D.b.h. class	49-tree plots	0.2-ha plots	49-tree plots	0.2-ha plots	49-tree plots	0.2 ha plots	49-tree plots	0.2-ha plots	49-tree plots	0.2-ha plots
Cm	Number per hectare									
					DOUGLAS-FIR					
5	488	283	30	14	--	9	--	--	--	--
10	2,319	1,274	519	515	81	112	23	8	5	--
15	2,136	961	671	891	244	228	38	17	29	12
20	671	319	702	594	203	406	69	104	54	52
25	--	51	92	176	393	303	221	212	122	88
30	--	10	30	23	122	70	198	224	122	124
35	--	--	--	--	14	--	46	42	63	100
40	--	--	--	--	--	--	--	12	24	16
							--	--	--	5
Totals	5,614	2,898	2,044	2,215	1,058	1,128	595	619	425	391
					WESTERN REDCEDAR					
5	2,380		30		--		--		--	
10	2,685		458		95		76		10	
15	1,342		854		203		84		54	
20	122		976		230		114		44	
25	122		61		217		191		103	
30	--		30		217		122		127	
35	--		--		68		61		83	
40	--		--		14		--		20	
Totals	6,651		2,410		1,044		648		439	
					WESTERN HEMLOCK					
5	1,586	1606	305		54		8		15	
10	2,258	2701	732		285		76		39	
15	732	787	549		637		206		117	
20	--	47	244		163		221		73	
25	--	--	30		68		107		49	
Totals	4,576	5,140	1,861		1,207		618		293	

-- = not applicable.
1/ Totals may not equal sum of column entries because all numbers are rounded to the nearest whole tree.

Percentage-of-frequency distributions at age 25 were similar in the 49-tree-plot and 0.2-ha-plot trials; this was especially true of both Douglas-fir and hemlock stands planted at the 0.9-m spacing (fig. 13). The greatest disparities between the 49-tree-plot and 0.2-ha-plot trials for Douglas-fir occurred at the 2.7- and 4.6-m spacings. The similarity of the percentage distribution for the 49-tree-plot and 0.2-ha-plot trials for Douglas-fir and western hemlock at the 0.9-m spacing suggests that loss of many trees due to snow press had little effect on relative diameter distribution but, instead, reduced the area actually occupied by the trees.

Shapes of cumulated d.b.h. distribution curves are generally consistent; there are a few incongruities, especially for cedar and hemlock. We believe deviations from the general patterns shown in figure 13 reflect variations in site or other factors unrelated to spacing; some merely reflect the irregularities associated with small sample sizes.

Basal area per hectare —For all three species, the wider the spacing the less the basal area per hectare. Differences among spacings widened initially but, for the four wider spacings, are now generally stabilized (fig. 14). The superiority of the 0.9-m spacing diminished as competition pressure reduced growth rates and increased mortality. Net growth at the 0.9-m spacing slowed markedly, while that at wide spacings apparently accelerated.

All per-hectare yield values (number of trees, basal area, total-stem volume, and merchantable volume) were strongly influenced by survival as well as by diameter; survival and diameter trends are presented together in figure 15. Diameters were influenced to a much lesser extent by variations in survival. A look at survival percentages reveals the reasons for irregularities in other stand parameters. Because some variation in survival was the result of factors unrelated to spacing and occurred irregularly over time, one must be careful in interpreting differences in basal area and volumes among species and plots.

The slowdown in net basal area growth of Douglas-fir after age 17 at the 0.9-m spacing in the 49-tree-plot trial was associated with a slight increase in rate of mortality (number per hectare) and a slight decrease in the rate of diameter growth. The lower level of basal area at age 18 at the 0.9-m spacing in the 0.2-ha-plot trial was associated with about one-half the number of trees per hectare present in the 49-tree-plot trial. Differences between the 49-tree-plot and the 0.2-ha-plot trials for other spacings were associated mostly with differences in **pre**establishment mortality, and to a lesser extent with differences in **post**establishment mortality and in rates of diameter growth.

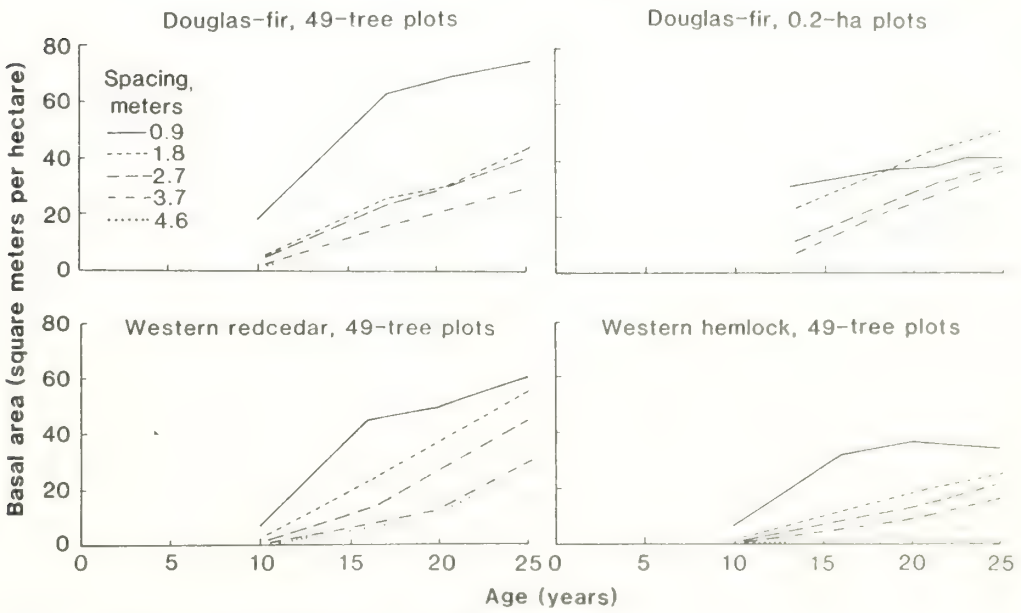


Figure 14—Basal area per hectare, by age and by spacing, of Douglas-fir in the 49-tree-plot and 0.2-ha-plot trials and of western redcedar and western hemlock in the 49-tree-plot trial.

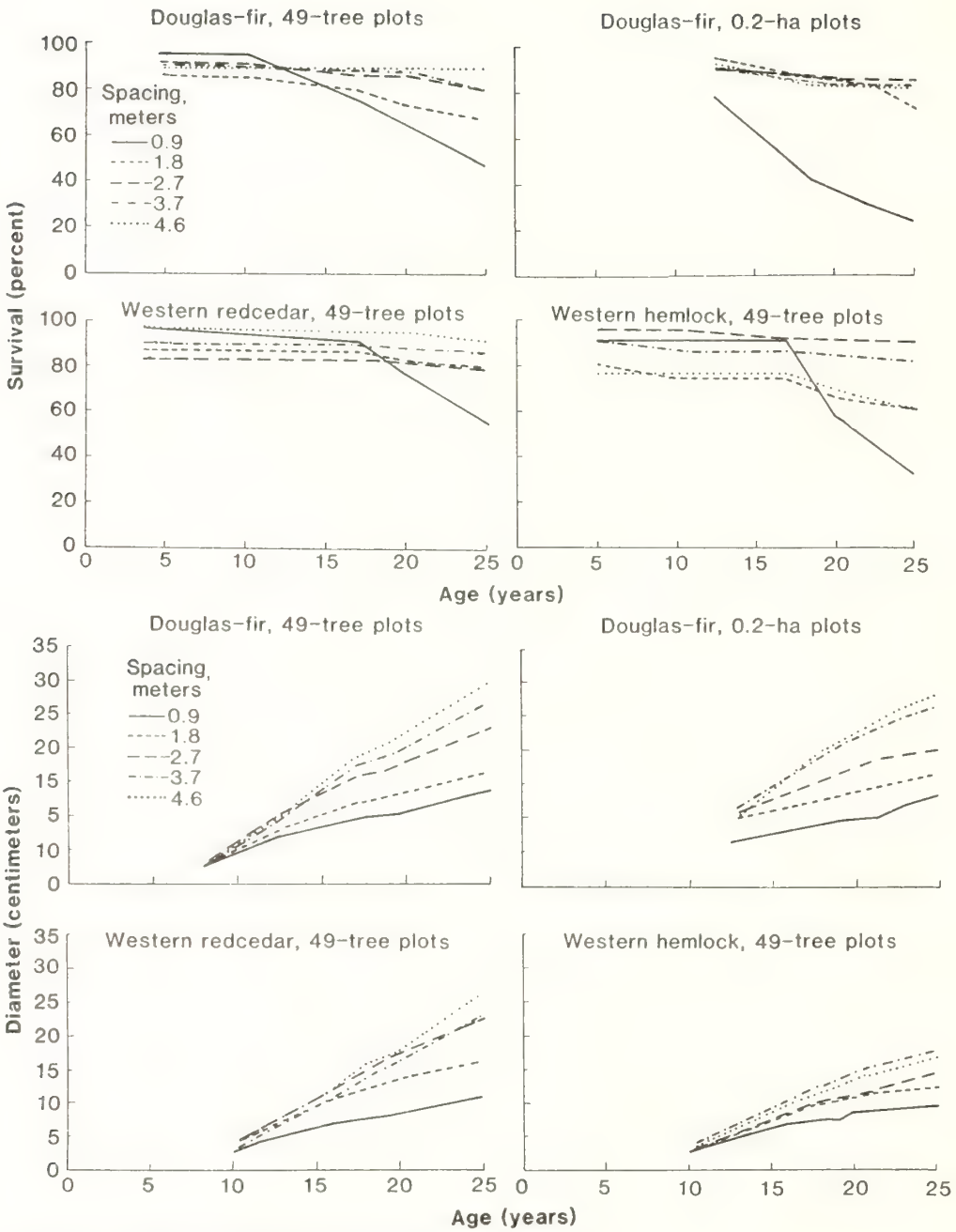


Figure 15—Survival percentage and average d.b.h., by age and by spacing, of Douglas-fir in the 49-tree-plot and 0.2-ha-plot trials and of western redcedar and western hemlock in the 49-tree-plot trial.

For cedar and hemlock, the flattening of basal area curves for the 0.9-m spacing after age 16 was associated with rapid rates of mortality. The minor irregularity thereafter for cedar was associated with small differences in rates of both mortality and diameter growth, and that for hemlock was associated with substantial differences in rates of mortality. Trends for other spacings were associated with the number per hectare and average diameter.

Total-stem volume—Volume also decreased with increased spacing (fig. 16). For all three species, patterns of volume growth are quite similar to the basal area trends, except for exaggeration of the irregularity for cedar at the 0.9-m spacing and greater acceleration at the wider spacings with increasing age.

Net volume growth generally accelerated. For Douglas-fir, the rate steadily increased at all except the 0.9-m spacing; the rate of increase slowed markedly at the 0.9-m spacing, mostly because of heavy mortality. The trends for cedar were similar to those for Douglas-fir (except for the 0.9-m spacing, which reflects differences in mortality). For hemlock, stands at 1.8-m, 2.7-m, and 3.7-m spacings grew at about the same rate between ages 20 and 25; stands at the 4.6-m spacing grew more poorly, which was consistent with poorer crown development and heavy mortality.

Merchantable volume — Except for the 0.9-m spacing, trends for merchantable volume (cubic volume of the portion of the stem between a 30-cm stump height and a 10-cm top d.i.b. (diameter inside bark)) are similar to trends for total-stem volume (fig. 17). Trends shown for the 0.9-m spacing are different and, superficially, do not appear to be compatible with the other trends; merchantable volume did not begin to accumulate until much later at close spacings, but it then accumulated rapidly because of ingrowth.

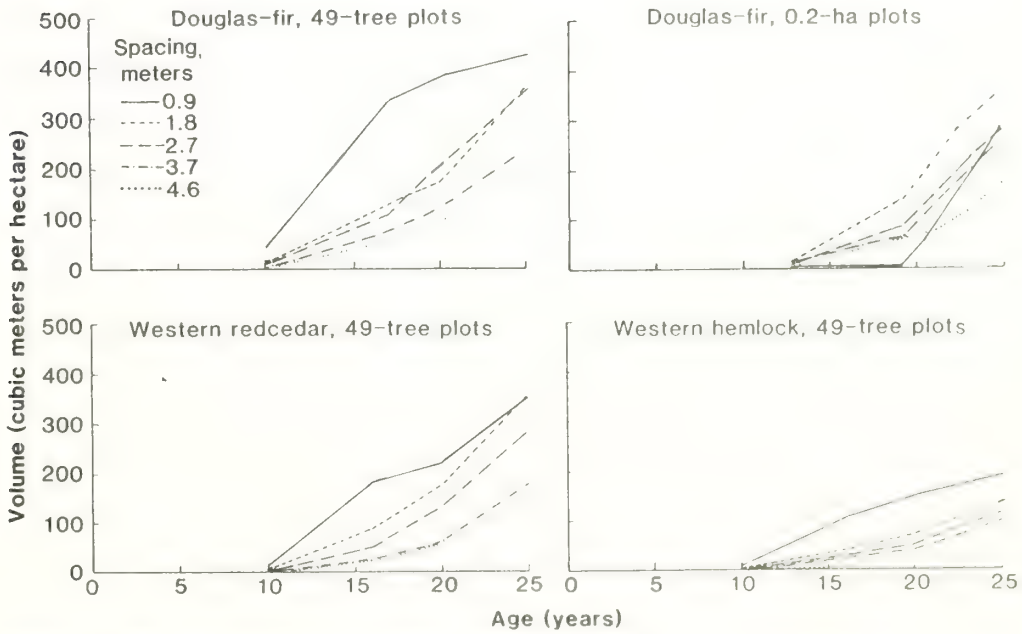


Figure 16—Total-stem cubic volume per hectare, by age and by spacing, of Douglas-fir in the 49-tree-plot and 0.2-ha-plot trials and of western redcedar and western hemlock in the 49-tree-plot trial.

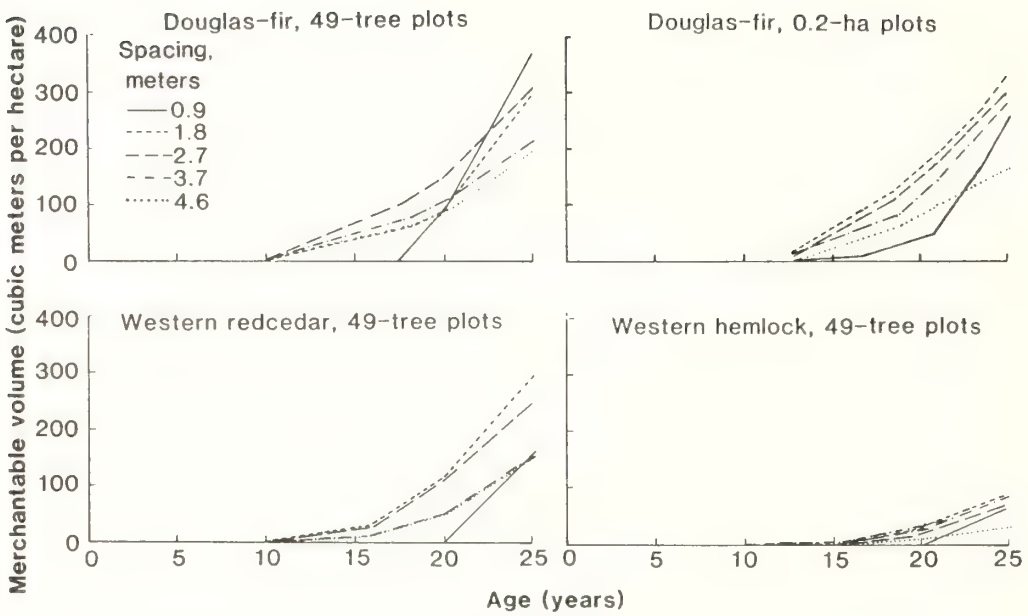


Figure 17—Merchantable cubic volume per hectare, by age and by spacing, of Douglas-fir in the 49-tree-plot and 0.2-ha-plot trials and of western redcedar and western hemlock in the 49-tree-plot trial. Volume is for the portion of stem between a 30-cm stump height and a 10-cm top d.i.b.

The Rectangularity Trial

Survival and mortality — Early survival of trees planted in the rectangularity trial was generally rather poor. An average of more than 30 percent of the trees died by age 8. Dead seedlings were not replaced. On almost all plots, most early mortality was concentrated in patches; survival was good on portions of most plots. An aerial photograph taken in 1973 clearly showed many patches of mortality, which were quite large on some plots. Some of these patches left completely unoccupied areas and probably benefited the trees bordering them. In other cases, individual trees or small groups of trees were surrounded by large openings, which favored growth of these trees.

By looking at results from the 49-tree-plot and 0.2-ha-plot trials, one might expect that all mortality before age 8 was due to factors unrelated to spacing. The distribution of mortality, evident on the 1973 aerial photo, also supports this conclusion.

After age 8, heavy losses occurred in the pure Douglas-fir stands that were planted at the 0.9- and 1.4-m spacings. These losses were due mostly to snow press. At age 20, only 14 percent of the trees at the 0.9-m spacing and 26 percent of those at the 1.4-m spacing were still alive. Survival was better in the mixed than in the pure stands, perhaps because the irregular canopy reduced snow accumulations. At wider spacings, an average of 63 percent of the trees in the pure Douglas-fir stand survived, whereas 70 percent of the Douglas-fir and 58 percent of the hemlock in the mixed stand survived (table 5).

Table 5—Survival, mean d.b.h., and mean height at age 20 for the rectangularity trial, by spacing and by species

Initial spacing	Treatment 1/	Initial 2/ number per hectare	Pure Douglas-fir			Mixed stand					
						Douglas-fir			Western hemlock		
			Survival	D.b.h.	Height	Survival	D.b.h.	Height	Survival	D.b.h.	Height
Meters			Percent	Cm	Meters	Percent	Cm	Meters	Percent	Cm	Meters
0.9 by 0.9	UT	11,961	14	11.0	14.1	59	11.3	15.1	45	8.0	[illegible]
	1/3T	7,974	--	--	--	76	10.8	14.3	74	10.3	13.8
	1/2T	5,980	--	--	--	79	13.7	15.7	71	10.7	13.6
1.4 by 1.4	UT	5,316	26	12.1	14.7	69	13.3	16.7	66	12.9	14.8
	1/3T	3,544	--	--	-	83	18.4	18.7	33	[illegible]	14.8
	1/2T	2,658	--	--	-	72	17.9	17.9	[illegible]	12.9	15.6
1.8 by 1.8		2,990	70	14.2	15.1	85	17.6	16.2	67	[illegible]	[illegible]
1.8 by 2.7		1,994	83	15.6	15.8	90	[illegible]	15.6	39	13.4	12.6
1.8 by 3.7		1,495	64	18.9	16.2	60	[illegible]	15.4	52	14.0	12.7
2.7 by 2.7		1,329	56	19.5	15.6	69	20.5	14.9	61	17.1	15.7
2.7 by 3.7		997	49	19.2	14.2	80	21.9	16.0	72	[illegible]	13.5
2.7 by 4.6		797	53	21.6	15.4	79	23.7	16.2	49	[illegible]	15.5
2.7 by 5.5		665	64	21.3	15.3	61	22.9	16.0	57	16.2	12.9
Averages 1.8-m and wider spacings:			63		15.4	70		15.8	57		14.0

-- = not applicable.
1/ UT = unthinned; 1/3T = every 3d row cut; 1/2T = every 2d row cut.
2/ Nominal number per hectare planted or left after thinning at age 10.

In the mixed Douglas-fir/western hemlock stands, portions of plots planted at the 0.9- and 1.4-m spacings were thinned at age 10. Data for the unthinned third of each plot suggest that between ages 10 and 20 the stand at the 0.9-m spacing lost about 33 percent of its trees and the stand at the 1.4-m spacing lost about 16 percent. Apparent mortality in thinned portions varied, but was substantial in some instances; it was much less than in the unthinned portion at the 0.9-m spacing, but not at the 1.4-m spacing (table 6, a and b).

Height — At age 8, the average height of all trees was 3.3 m. Averages were virtually the same for both the pure Douglas-fir and the mixed Douglas-fir/western hemlock blocks, and for both species within the mixed block. Average heights on individual plots varied irregularly around this overall average—from 2.5 to 4.0 m for Douglas-fir and from 2.3 to 4.3 m for hemlock (fig. 18). In the mixed stand, Douglas-fir was taller than hemlock on six plots and hemlock was taller than Douglas-fir on three plots.

Over the next 12 years (to age 20), Douglas-fir consistently grew more than hemlock. The apparent increase in average height between ages 8 and 20 ranged from 11.0 to 15.5 m for Douglas-fir and from 9.7 to 12.8 m for western hemlock. There was no relation of height growth to either the spacing or the height at age 8. Heights at age 20 averaged 15.6 m for Douglas-fir and 14.0 m for hemlock (table 5). Variations around these averages were highly erratic and overshadowed any possible effects of spacing (fig. 18).

Table 6A—Apparent[1] cumulative mortality (percentage of nominal number planted or left after thinning), by initial spacing and by age, since time of *planting* on unthinned and thinned subplots in mixed Douglas-fir/hemlock stands in the rectangularity trial

Initial spacing	Treatment 2/	Douglas-fir, by age				Western hemlock, by age			
		10	11	17	20	10	11	17	20
Meters		Percent							
0.9 by 0.9	UT	15	18	30	41	31	31	41	55
0.9 by 0.9	1/3T	(13)	13	15	24	25	25	25	26
0.9 by 0.9	1/2T	(8)	8	17	21	(25)	(25)	25	29
1.4 by 1.4	UT	16	16	25	31	25	27	33	34
1.4 by 1.4	1/3T	(8)	(8)	8	17	58	63	63	67
1.4 by 1.4	1/2T	12	16	25	28	16	16	22	28

1/ Derived from numbers of surviving trees tallied at each age.
2/ UT = unthinned; 1/3T = every 3d row cut; 1/2T = every 2d row cut.

Table 6B—Apparent[1] cumulative mortality (percentage of actual number left after thinning at age 10), by initial spacing and by age, since time of *thinning* on unthinned and thinned subplots in mixed Douglas-fir/hemlock stands in the rectangularity trial

Initial Spacing	Treatment 2/	Douglas-fir, by age			Western hemlock, by age		
		11	17	20	11	17	20
Meters		Percent					
0.9 by 0.9	UT	3	17	31	0	15	35
0.9 by 0.9	1/3T	(0)	2	12	0	0	2
0.9 by 0.9	1/2T	(0)	10	15	(0)	(0)	5
1.4 by 1.4	UT	0	11	19	2	10	13
1.4 by 1.4	1/3T	(0)	(0)	9	10	10	20
1.4 by 1.4	1/2T	4	14	18	0	7	15

1/ Derived from numbers of surviving trees tallied at each age.
2/ UT = unthinned; 1/3T = every 3d row cut; 1/2T = every 2d row cut.

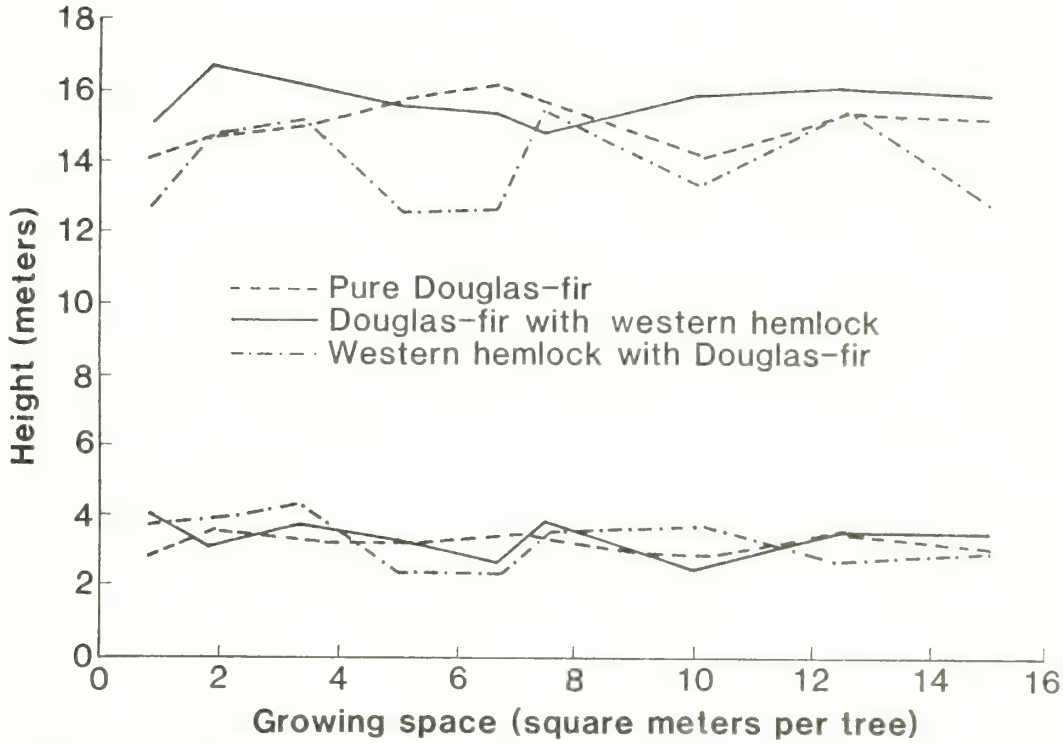


Figure 18—Average heights of Douglas-fir and western hemlock at ages 8 and 20, by nominal average growing space per tree, in the pure Douglas-fir and Douglas-fir/western hemlock blocks of the rectangularity trial.

In the mixed Douglas-fir/hemlock stands, attained height of Douglas-fir was taller than that of hemlock on all but one plot; the difference averaged 14 percent and ranged from -5 to 26 percent. These differences also bore no clear relation to spacing.

Average height of Douglas-fir, across all spacings, was 3 percent greater in the mixed stand than in the pure stand; at three spacings, however, Douglas-fir trees were shorter in the mixed than in the pure stands. Differences among plots were probably related primarily to site variation.

The heights of Douglas-fir in the rectangularity trial were a little greater (5 percent) than those at age 20 in the 49-tree-plot and 0.2-ha-plot trials, which averaged about 14.6 m. The heights of hemlock were much greater (49 percent) than those at age 20 in the 49-tree-plot trial, which averaged only about 9.4 m (table 7).

Table 7—Average height and the range of heights at age 20 for trees planted at spacings wider than 3 m² per tree, by species and by trial

Species and trial	Height	
	Average	Range
	- - - - - - -Meters - - - - - - -	
Douglas-fir:		
49-tree plots	14.6	13.4-15.4
0.2-ha plots 1/	14.8	14.6-15.2
Rectangularity, pure	15.4	14.2-16.2
Rectangularity, with WH 2/	15.8	14.9-16.2
Nelder, pure	14.2	13.8-14.7
Nelder, mixed	14.4	13.5-15.0
Variable-block (age 22)	15.6	--
Western redcedar:		
49-tree plots	10.4	9.2-11.4
Nelder, mixed	6.6	4.8- 8.9
Variable-block (age 22)	5.7	--
Western hemlock:		
49-tree plots	9.4	8.9-10.1
Rectangularity, with DF 3/	14.0	12.6-15.7
Nelder, mixed	10.7	9.4-12.1
Variable-block (age 22)	13.5	13.1-13.9
Sitka spruce:		
Nelder, mixed	6.0	5.2- 6.8
Variable-block (age 22)	4.1	--

-- = not applicable.
1/ Interpolated between ages 19 and 23.
2/ With WH = grown with western hemlock in alternating rows.
3/ With DF = grown with Douglas-fir in alternating rows.

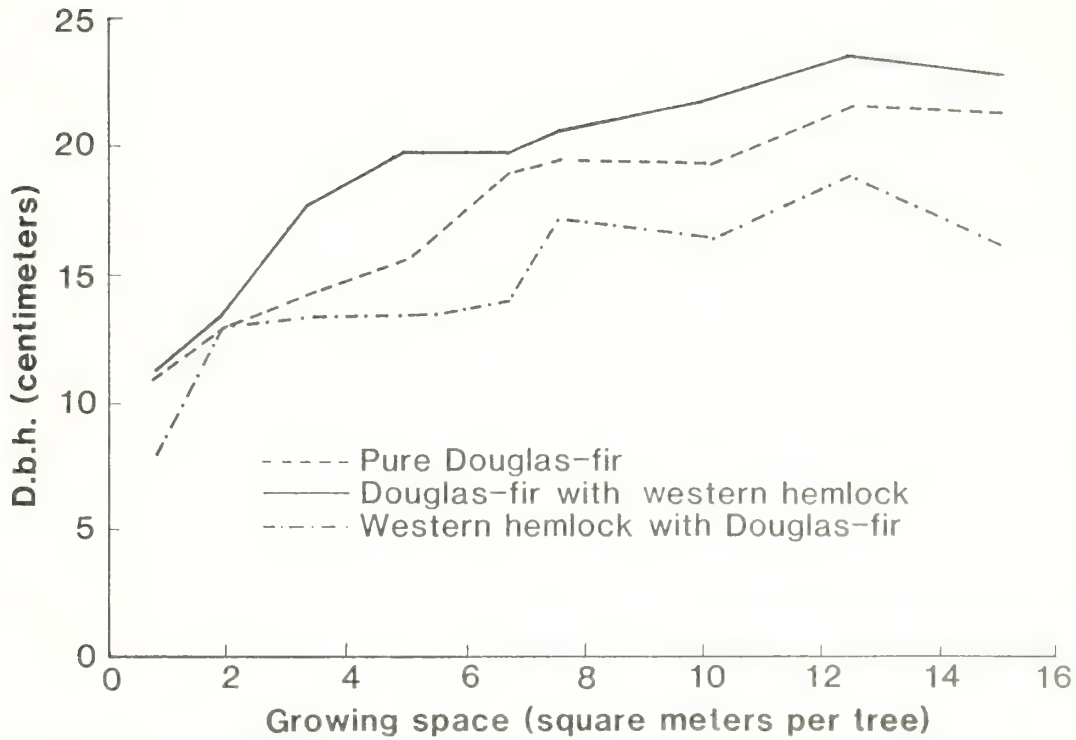


Figure 19—Average diameters of Douglas-fir and western hemlock at age 20, by nominal average growing space per tree, in the pure Douglas-fir and Douglas-fir/western hemlock blocks of the rectangularity trial.

Diameter — Average d.b.h. of Douglas-fir at age 20 increased strongly with increased spacing for spacings of 0.9 by 0.9 m through 2.7 by 1.8 m (table 5). Additional increase with progressively wider spacing was less and was somewhat erratic (fig. 19). In both the pure Douglas-fir stands and the mixed Douglas-fir/hemlock stands, the maximum average d.b.h. for both species occurred at the next to widest spacing (4.6 by 2.7 m). The slight falloff at the 5.5- by 2.7-m spacing was probably happenstance but might have been associated with heavy brush.

In the mixed Douglas-fir/western hemlock stands, the attained average d.b.h. of Douglas-fir was consistently greater than that of hemlock. Mean d.b.h. of Douglas-fir averaged 32 percent larger than that of hemlock; by plot, differences between the two species ranged up to 48 percent. These differences showed no relation to spacing (fig. 19).

Average d.b.h. of Douglas-fir at age 20 was consistently larger for a given plantation spacing in the mixed Douglas-fir/hemlock stands than in the pure Douglas-fir stands. This larger d.b.h. of Douglas-fir in the mixed stands, for a given nominal spacing, reflects the additional growing space available to Douglas-fir because of the slower growth (and poorer survival) of adjacent hemlock.

Average d.b.h. as a function of nominal growing space per tree in the pure Douglas-fir stands of the rectangularity trial was comparable with that in the 49-tree-plot and 0.2-ha-plot trials but was generally a little larger (table 8). Possible effects of spatial pattern were overshadowed by other sources of variation.

Table 8—Comparison among the five trials, and among species,[1] of height and average d.b.h at age 20, by spacing (or average growing space per tree)

A. 49-TREE-PLOT AND 0.2-HA-PLOT TRIALS

Spacing	Average growing space	DF, 49-tree		DF, 0.2-ha 2/		WRC, 49-tree		WH, 49-tree	
		Height	D.b.h.	Height	D.b.h.	Height	D.b.h.	Height	D.b.h.
meters	m^2/tree	meters	cm	meters	cm	meters	cm	meters	cm
0.9 by 0.9	0.84	13.6	11.0	14.2	9.9	8.9	8.7	9.0	8.7
		13.2	10.2			7.6	8.0	9.1	7.8
1.8 by 1.8	3.35	13.7	13.0	14.6	14.0	9.3	13.7	9.4	11.1
		13.4	13.5			9.9	13.8	9.0	11.4
2.7 by 2.7	7.53	14.6	17.1	15.2	17.5	10.8	16.5	8.9	11.1
		15.3	18.7			11.4	18.4	9.6	11.4
3.7 by 3.7	13.38	15.2	21.0	14.7	21.8	9.2	13.9	9.5	13.7
		14.8	19.6			10.7	18.4	9.6	15.9
4.6 by 4.6	20.91	15.4	22.3	14.7	22.6	10.8	17.2	10.1	14.6
		14.6	22.6			10.8	18.6	9.3	12.7

B. RECTANGULARITY TRIAL

Spacing	Average growing space	Pure DF		DF w/WH		WH w/DF	
		Height	D.b.h.	Height	D.b.h.	Height	D.b.h.
meters	m^2/tree	meters	cm	meters	cm	meters	cm
0.9 by 0.9	0.84	14.1	11.0	15.1	11.3	12.7	8.0
1.4 by 1.4	1.88	14.7	12.1	16.7	13.3	14.8	12.9
1.8 by 1.8	3.35	15.1	14.2	16.2	17.6	15.2	13.4
1.8 by 2.7	5.02	15.8	15.6	15.6	19.8	12.6	13.4
1.8 by 3.7	6.69	16.2	18.9	15.4	19.8	12.7	14.0
2.7 by 2.7	7.53	15.6	19.5	14.9	20.6	15.7	17.1
2.7 by 3.7	10.04	14.2	19.2	16.0	21.9	13.5	16.3
2.7 by 4.6	12.55	15.4	21.6	16.2	23.7	15.5	18.8
2.7 by 5.5	15.06	15.3	21.3	16.0	22.9	12.9	16.2

C. NELDER-PLOT TRIAL

Arc	Average growing space	DF, plot 1		DF, plot 2		WH, plot 2		WRC, plot 2		SS, plot 2	
		Height	D.b.h.	Height	D.b.h.	Height	D.b.h.	Height	D.b.h.	Height	D.b.h.
meters	m²/tree	meters	cm	meters	cm	meters	cm	meters	cm	meters	cm
1G 3/	--	13.1	11.3	15.1	17.2	12.5	10.5	4.4	3.5	5.8	6.7
2	0.83	13.4	10.1	14.5	15.6	10.1	8.7	3.4	4.1	6.3	6.4
3	1.08	13.0	9.7	13.5	12.5	10.5	9.2	5.2	5.0	6.9	8.9
4	1.35	13.0	9.2	14.6	13.0	10.1	10.6	7.2	7.2	7.0	8.6
5	1.72	12.9	10.9	13.3	12.8	13.1	17.1	5.4	5.5	6.5	8.3
6	2.13	13.2	10.6	14.8	16.2	10.7	9.0	6.5	6.9	6.0	8.2
7	2.82	13.3	11.5	14.8	16.2	12.2	13.0	7.7	10.6	6.9	12.5
8	3.57	14.5	14.2	14.7	18.0	11.6	13.5	6.0	11.5	6.6	10.7
9	4.54	14.4	14.0	15.0	19.6	11.7	14.9	7.2	9.7	6.6	12.7
10	5.76	14.7	15.8	14.4	19.7	9.4	12.2	6.8	9.1	6.8	14.8
11	7.34	13.9	16.0	14.7	21.2	9.4	12.1	8.9	13.3	6.2	12.4
12	9.30	13.8	16.8	14.3	20.0	10.7	14.9	7.2	9.3	6.0	14.7
13	11.83	14.2	19.0	14.4	23.0	12.1	17.6	6.1	9.7	6.0	12.8
14	15.21	14.3	20.4	14.1	22.3	9.5	14.5	4.8	7.1	5.5	13.7
15	19.27	14.4	21.3	14.7	23.8	10.2	14.1	5.1	5.9	5.3	11.1
16	24.40	14.0	20.9	13.5	21.3	11.5	16.0	7.4	10.7	5.2	11.8
17G 3/	--	14.0	20.2	14.7	25.1	10.6	14.4	7.4	10.6	5.8	12.0

D. VARIABLE-BLOCK TRIAL

Spacing	Average growing space	DF		WH		WRC		SS	
		Height	D.b.h.	Height	D.b.h.	Height	D.b.h.	Height	D.b.h.
meters	m²/tree	meters	cm	meters	cm	meters	cm	meters	cm
0.9 by 0.9	0.84	13.0	8.9	--	--	?	4.9	--	--
1.8 by 1.8	3.35	15.6	12.1	--	--	5.7	6.9	4.1	7.3
2.7 by 2.7	7.53	--	--	13.1	14.9	--	--	--	--
4.6 by 4.6	20.91	15.6	22.0	13.9	17.0	--	--	--	--

-- = not applicable.
? = not available.
1/ Species: DF = Douglas-fir, WRC = western redcedar, WH = western hemlock, SS = Sitka spruce; w/ means grown in mixture with.
2/ Interpolated between ages 19 and 23 for height on 0.2-ha plots.
3/ G = guard arc.

The effect on diameter growth of respacing stands at age 10 in those Douglas-fir/hemlock stands planted at the 0.9- and 1.4-m spacings was apparently about the same as if the stands had initially been planted at the spacings to which they were respaced. Responses differed somewhat erratically, however, by both initial spacing and species (fig. 20).

Stem form — For any given nominal spacing, western hemlock generally had the highest H-to-D ratio, and Douglas-fir in the mixed stand had the lowest. The ratios for Douglas-fir in the pure stand were intermediate, but generally were closer to those for Douglas-fir in the mixed stand. In general, the ratio declined (that is, stem taper increased) with increased growing space; the lower ratios for Douglas-fir in the mixed stand, relative to the pure stand, are consistent with this (fig. 21).

CLEMSON UNIVERSITY LIBRARY
PUBLIC DOCUMENTS DEPT.

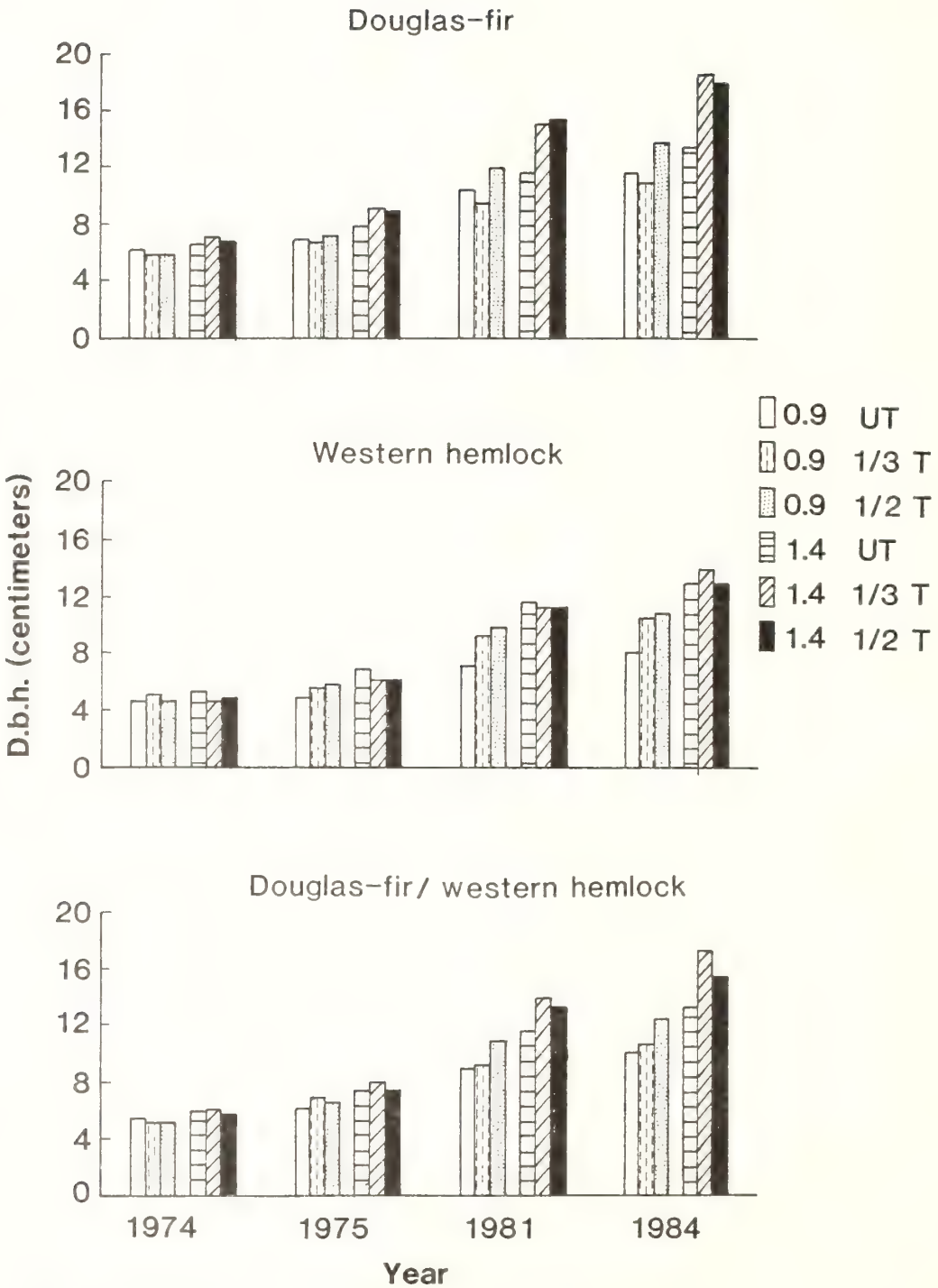


Figure 20—Average diameters of Douglas-fir, western hemlock, and the two species combined, by age and treatment (initial spacing and thinning), in the mixed Douglas-fir/western hemlock rectangularity trial plots that were thinned at age 10. UT = unthinned; 1/3 T = every third row cut; and 1/2 T = every second row cut.

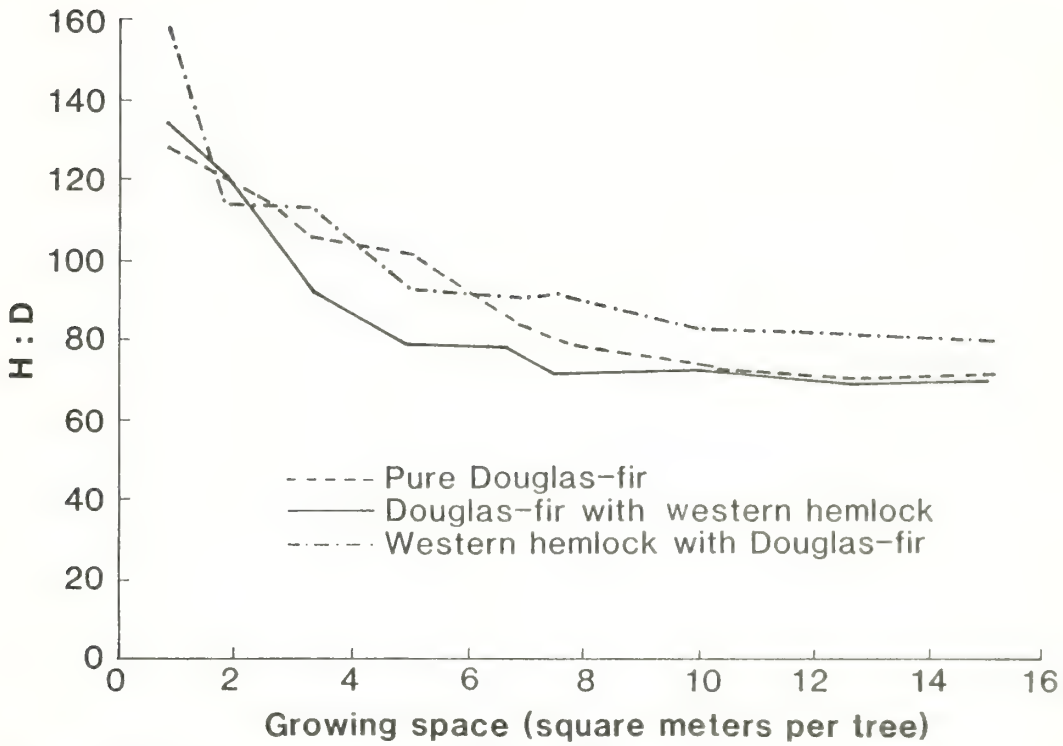


Figure 21—Ratio of height to d.b.h. (H:D) at age 20, for trees of average height and d.b.h., for pure Douglas-fir and for Douglas-fir and western hemlock grown in mixture in the rectangularity trial.

The Nelder-Plot Trial

Nelder-plot 1 (pure Douglas-fir) — Nelder-plot 1 showed clear trends of increased d.b.h. with increased spacing for spacings wider than about 1.5 m (table 9). Comparison of average annual d.b.h. growth for two successive periods, ages 11-15 and ages 15-20, showed that for spacings wider than about 1.5 m, differences in favor of the wider spacings increased over time at a substantial rate.

Nelder-plot 1 also showed depressed height growth at spacings of less than about 1.8 m; at spacings wider than this, however, height varied irregularly and showed no clear relation to spacing. Between ages 15 and 20, height growth became even more depressed at spacings of less than about 2 m; but there was no clear effect of spacing at spacings wider than 2 m.

The slightly greater growth, in both d.b.h. and height, on inner arcs may be associated with the position of those arcs near the "eye" of the plot; this suggests that a one-arc buffer is insufficient. Also, trees on arc 2 were cut on two of the three quadrants and those on arc 4 were cut on one quadrant in 1974. This cutting on arcs 2 and 4 released some trees on arcs 1, 3, and 5. Data shown for those latter three arcs therefore represent a combination of initial spacing effects and effects of release, and they are not comparable to data from other arcs.

Survival on this plot was excellent and averaged 93 percent (exclusive of arcs 2 and 4).

Table 9—Mean d.b.h. and height of Douglas-fir at age 20 and periodic annual growth between ages 11-15 and 15-20 in Nelder-plot 1 (spokes 1-36), by arc and spacing

Arc number	Spacing	Number of trees	Age 20		Annual d.b.h. growth			Annual height growth		
			D.b.h.	Height	Age 11-15	Age 15-20	Ratio	Age 11-15	Age 15-20	Ratio
	meters		cm	m	centimeters		percent	- - meters - -		percent
1G 1/	--	34	11.3	13.1	0.75	0.51	68	0.98	0.72	74
2	2/ 0.91	10	10.1	13.4	.65	.39	60	1.00	.84	84
3	1.04	33	9.7	13.0	.60	.38	64	1.00	.72	72
4	2/ 1.16	19	9.2	13.0	.58	.31	55	1.00	.70	70
5	1.31	30	10.9	12.9	.73	.40	55	1.00	.66	66
6	1.46	32	10.6	13.2	.75	.35	47	1.02	.74	72
7	1.68	32	11.5	13.3	.80	.39	49	1.00	.74	74
8	1.89	32	14.2	14.5	1.01	.63	63	1.15	.84	73
9	2.13	32	14.0	14.4	1.08	.60	55	1.05	.92	88
10	2.40	33	15.8	14.7	1.25	.81	65	1.12	.92	82
11	2.71	35	16.0	13.9	1.32	.84	63	1.05	.88	84
12	3.05	34	16.8	13.8	1.30	1.02	78	1.00	.88	88
13	3.44	35	19.0	14.2	1.53	1.19	78	1.10	.88	80
14	3.90	35	20.4	14.3	1.56	1.38	88	1.05	.88	84
15	4.39	35	21.2	14.4	1.68	1.55	92	1.08	.90	84
16	4.94	35	20.9	14.0	1.60	1.59	99	1.00	.92	92
17G 1/	--	33	20.2	14.0	1.59	1.48	93	1.00	.90	90

-- = not applicable.
1/ G = guard arc.
2/ Thinned in 1974 (age 12). On arc 2, trees were cut on two quadrants; on arc 4, trees were cut on one quadrant.

Spacings on arcs 8, 11, 13/14, and 15/16 are comparable to the four wider spacings tested on the 49-tree-plot and the 0.2-ha-plot trials. Spacing on arc 2 would be comparable to the narrowest spacing tested in those trials if arc 1 had provided a sufficient buffer around the "eye" (table 8).

Analyses of increment cores and branches from the rectangularity component of Nelder-plot 1 showed no harmful effects of rectangularities up to 4:1 (6 m by 1.5 m) on boles to age 20.

Nelder-plot 2 (four species) — In Nelder-plot 2, Douglas-fir consistently grew the best, hemlock a distant second, spruce third, and cedar the poorest. Survival of Douglas-fir and Sitka spruce were quite good at 89 and 95 percent, respectively; however, survival of cedar and hemlock were poor at 60 and 44 percent, respectively. Because of this poor survival, the effective space available to many trees was much greater than that implied by the original plantation spacing.

As in Nelder plot 1 and the other trials, d.b.h. of Douglas-fir increased strongly with increased spacing (fig. 22). (Growth of trees on inner arcs benefited from the wide opening around the single tree in the center of the "eye.") On all arcs of Nelder-plot 2, trees attained a much larger average size than on the equivalent arcs in Nelder-plot 1 (fig. 23). Of the three contiguous rows of Douglas-fir, one always borders on hemlock and one on cedar. Because these latter two species grew so much more poorly than Douglas-fir, and had poor survival, the Douglas-fir trees had much more available growing space than trees on the equivalent arc in Neider-plot 1. It is apparent to one who looks down the rows that the trees in the rows bordering on cedar or hemlock are larger than trees in the middle row, especially at the closer spacings.

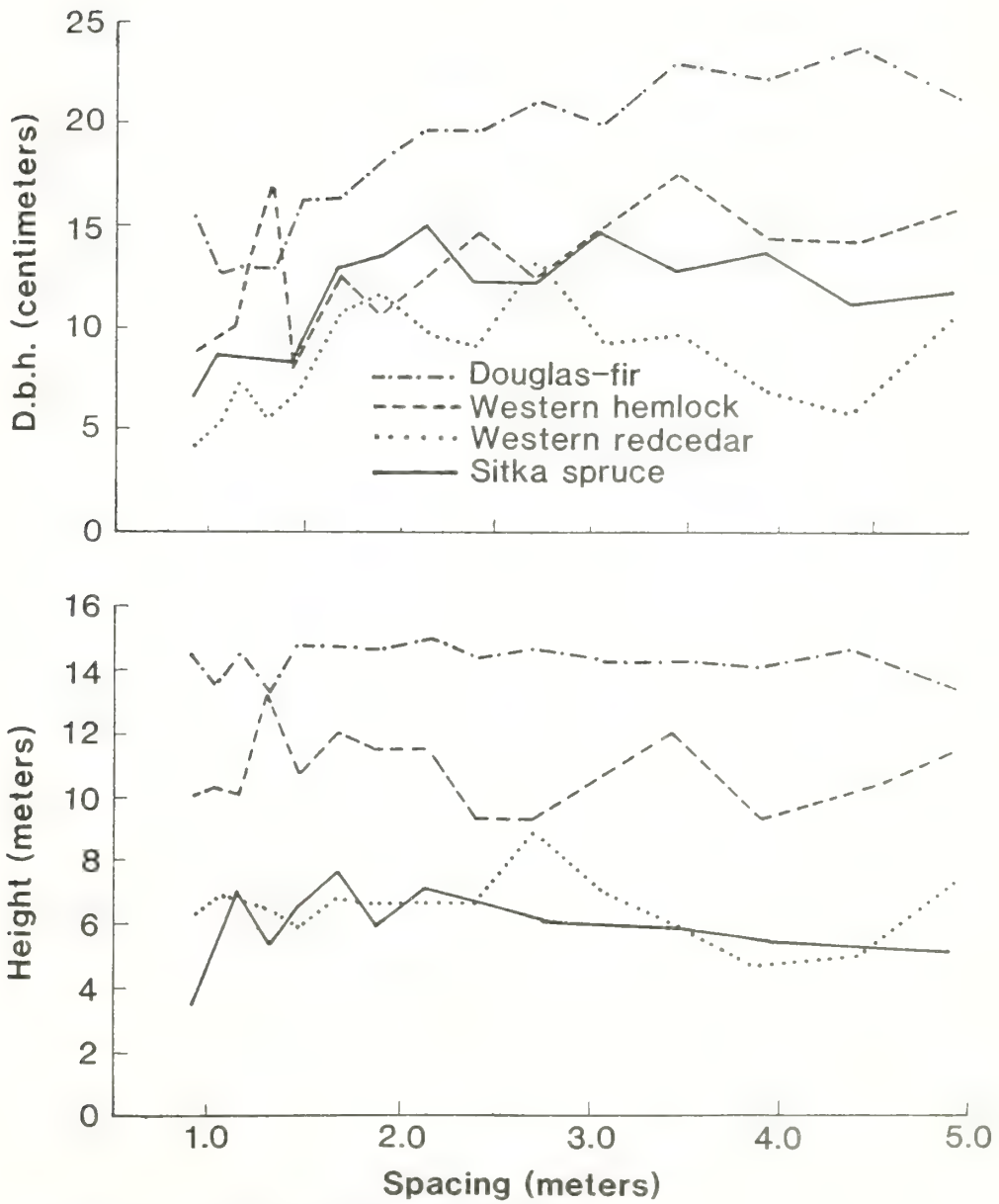


Figure 22—Average d.b.h. and height of Douglas-fir, western redcedar, western hemlock, and Sitka spruce at age 20, by spacing, in Nelder-plot 2.

Attained size of the other three species, unlike Douglas-fir, at age 20 did not bear such a strong relation to planted spacing (fig. 22). The d.b.h. of hemlock tended to increase only slightly with increased spacing, and the variation around the trend was much greater than for Douglas-fir. Spruce and cedar both exhibited an irregular pattern relative to spacing, perhaps because of weevil damage and deer browsing. Growth of both species was apparently depressed by close spacing (arcs 1-6), but it was little affected by spacing beyond arc 6 (1.5-m spacing).

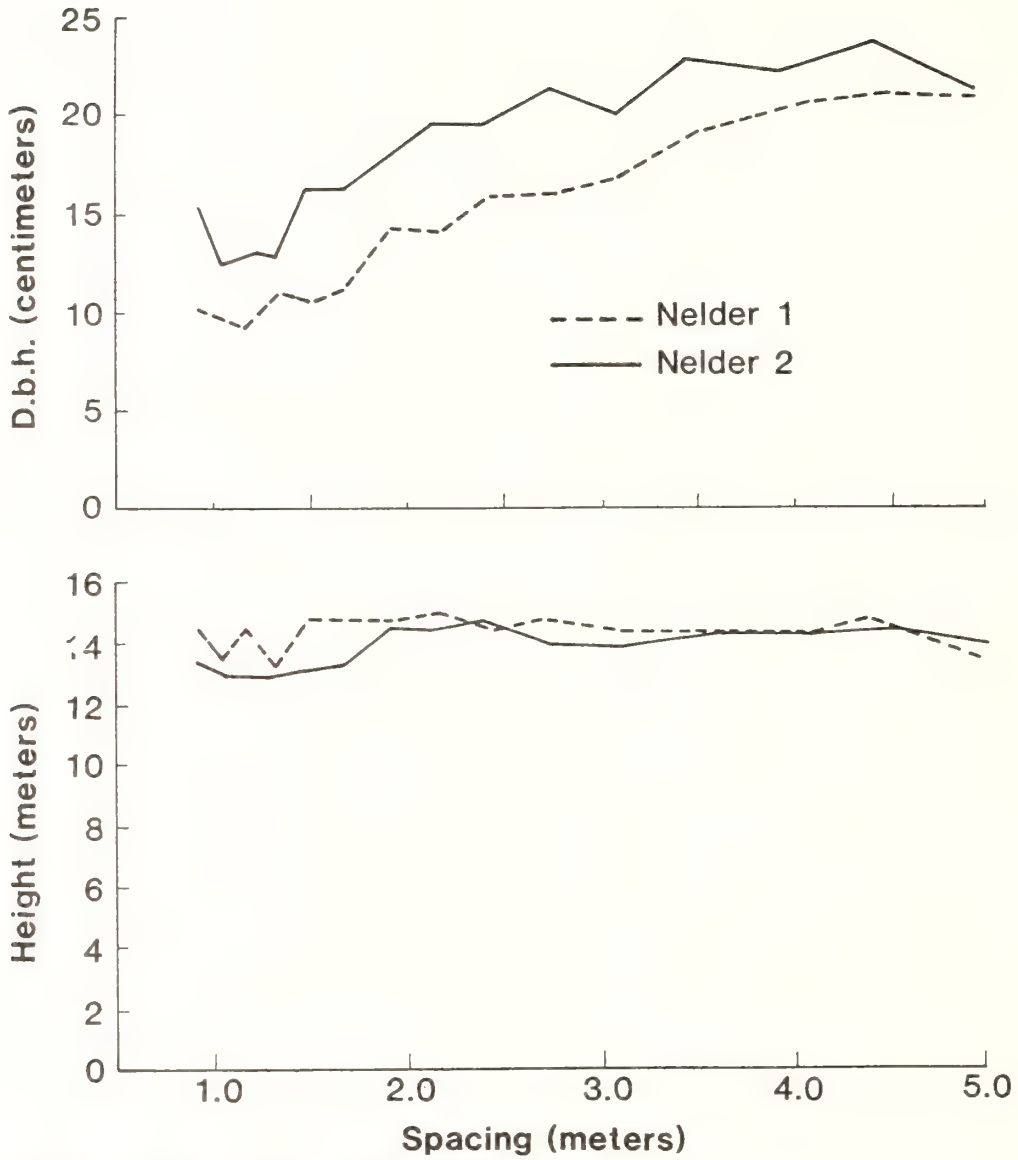


Figure 23—Average d.b.h. and height of Douglas-fir at age 20 by spacing, in Nelder-plots 1 and 2.

As in the other trials, height at age 20 appeared to be little affected by spacing. Average heights of Douglas-fir in Nelder-plot 2 were quite erratic on the inner seven arcs, whereas in Nelder-plot 1, heights were consistently depressed on these arcs (fig. 23). For arcs 8-16 (where spacings were wider than 1.8 m) there was little difference in heights between the two Nelder plots; averages differed by only 0.2 m or 1.4 percent. Height of cedar appeared to be depressed on the inner two or three arcs, but other than that, there was no consistent relation between height and spacing for cedar, hemlock, or spruce. Heights for arcs 8-16 averaged 14.4 m for Douglas-fir, 10.7 m for hemlock, 6.6 m for cedar, and 6.0 m for spruce.

The Variable-Block Trial

The variable-block trial illustrates what might be expected from operational plantings, which include neither replanting to replace dead seedlings nor control of invading vegetation. These stands were so heavily invaded by brush soon after planting that they were abandoned until 1984, when they were remeasured to determine how spacing influenced survival and growth under extreme competition from brush and noncommercial tree species.

Plot boundaries were fitted to areas on which each of the four species—Douglas-fir, western hemlock, western redcedar, and Sitka spruce—were believed to be most appropriate. Assignments of the species and the spacings at which they were planted were based on expected growth, as determined from ecological studies of their behavior in adjacent natural stands.

Despite the heavy, early brush competition, survival and growth were quite good for both Douglas-fir and western hemlock; growth of Douglas-fir was, on the average slightly better than that of hemlock (table 10). Western redcedar and Sitka spruce did much more poorly, primarily because of heavy deer browsing of cedar seedlings and severe weevil damage to spruce. The dense ground vegetation apparently did not have much deleterious effect on stand development.

Table 10—Survival and attained size of trees in the variable-block trial at age 22, by species and by spacing

	Planted		Survivors				Ingrowth
Species 1/	Spacing	Number per hectare	Percent	Number per hectare	Diameter	Height	Number per hectare
	Meters				Centimeters	Meters	
DF	0.91	11,960	25	2,954	8.9	13.0	94
	1.83	2,990	60	1,791	12.1	15.6	382
	4.57	478	67	322	22.0	15.6	53
WH	2.74	1,328	43	575	14.9	13.1	223
	4.57	478	63	301	17.0	13.9	544
WRC	.91	11,960	21	2,512	4.9	--	125
	1.83	2,990	34	1,032	6.9	5.7	186
SS	1.83	2,990	58	1,731	7.3	4.1	70

-- = not applicable.
1/ DF = Douglas-fir, WH = western hemlock, WRC = western redcedar, SS = Sitka spruce.

Mortality of Douglas-fir planted at the 0.9-m spacing was caused by a combination of suppression and snow press. In much of the area planted to Douglas-fir at the 4.6-m spacing, survival was better than the average indicates, and stands fully occupied the sites. Planting more trees to offset expected mortality, as is commonly suggested, would have resulted in overly dense stands and less individual tree growth; in areas where survival was poorer, stocking might have been slightly improved by planting more trees.

Natural regeneration of conifers was highly variable in age, species, and location within the 1.35-ha area. The number of such trees averaged 225 per ha, and plot averages varied irregularly from 53 to 544 per ha. The effects of this natural fill-in were, likewise, quite variable. In some cases, the fill-in provided a desirable supplement to the planted trees. At the other extreme, it sometimes resulted in an extremely high and undesirable level of stand density; this was especially true of a portion of the hemlock plot planted at the 4.6-m spacing, where natural fill-in created a stand density of about 10,000 trees per ha.

The effects of spacing shown in the variable-block trial were comparable to those in the other trials (table 8). Spacing had little effect on height growth but a substantial effect on diameter growth; close spacing may have slightly retarded height growth of Douglas-fir.

Other Factors to Consider

Edge effects may be important. Assessment at age 20 showed no significant differences, however, in rate of growth of edge trees vs. interior trees, probably because all the spacings were associated with other plantations that offered competition at the edges. There was also no distortion of bole shape of edge trees associated with unequal growth of crowns; edge trees did tend to lean slightly away from their more closely spaced neighbors. Elsewhere, in plantations that border on unplanted land (such as Wind River (Reukema 1979)), edge effects can be seen in much better growth of the two outer rows.

The 0.2-ha-plot trial has adequate buffer strips of 1 to 12 rows of trees. The 49-tree-plot trial has no buffers, so this is the trial most likely influenced by edge effects. It would therefore be better for some purposes to analyze only the interior 25 trees, or individual trees. The rectangularity trial has large plots, especially for the five wider spacings; thus, lack of buffers generally had a minimal effect on plot averages. Even though all trees were measured, for some purposes it would be better to analyze only those trees on interior plots. The Nelder plots have "guard arcs" (the innermost and outermost arcs), and Nelder-plot 1 also has "guard spokes" adjacent to the rectangularity quadrant. Effects seldom extended beyond one arc; all spokes were included in the reported averages in this paper. In Nelder-plot 2, only one row in each quadrant is flanked by trees of the same species; thus, a thorough interpretation would require consideration of the position of each tree. In the variable-block trial, most plots are comparable in size to those in the rectangularity trial, so the same comments apply.

Other sources of variation, not related to spacing, included (1) genetic and microsite variation—reflected by early differences in tree size, relation of subsequent growth to early height and diameter, brush development, and effects of site preparation on soil compaction; and (2) damage to seedlings or trees—including root rot pockets, snow press and wind damage, deer browsing of cedar, weevil damage to spruce, and squirrel damage to western hemlock.

Data showed that trees that had superior height or d.b.h. by about 10 years from seed retained that advantage to age 25 regardless of spacing and species. Trees that were initially small generally remained well below the average.

Plantations apparently have some advantages over natural stands. A comparison of height growth in the spacing plantations with heights from stem analyses of naturally established trees on the same area or in nearby stands showed that mean heights and top heights in the plantations started at higher levels and increased their advantage; the planted trees followed superior growth trajectories. Thus, apparent site indices were higher in the plantations.

The UBC spacing trials have provided convincing evidence that advantages of wide spacing increase over time, as has also been seen in the Wind River trial. Trees that showed early superiority at close spacings were not favored by self-thinning among their neighbors to the extent needed to overcome competition; trees released as a result of snow press of their neighbors did not grow fast enough to make up for their early poor crown development compared with trees spaced wide initially.

Relation to Targets

To provide proper perspective, results should be viewed relative to appropriate targets for the first commercial entry. The target is the stand density (level of competition) and average tree size to which one believes a stand should be grown before a thinning is needed to forestall mortality and to maintain tree vigor. Early spacing control determines stand characteristics at this stage of development. This target may be expressed in terms of number of trees per hectare and stand average diameter; the fewer the trees, the larger their size and the older the stand when the target is reached.

Target diameters suggested by Reukema (1975) range from less than 4 cm at the 0.9-m spacing to about 33 cm at the 4.6-m spacing. Corresponding ages at which these targets were reached in the 49-tree-plot and 0.2-ha-plot trials ranged from about age 9 at the 0.9-m spacing to age 22 or 23 at the 3.7-m spacing; it appears that the 4.6-m spacing will reach its target at about age 30. (The Wind River plantations reached target densities from about age 20 with 1.2-m spacing to age 41 with 3.7-m spacing.)

Stands that have only recently reached their target, or have not yet reached it, would be expected to have suffered little spacing-related mortality; the longer the time since the target was reached, the greater the amount of mortality expected. This trend was evident in these trials, but stands reached densities much higher than the suggested target level before substantial mortality occurred. Because trees in the UBC trials were relatively short for their d.b.h., perhaps target diameters should realistically be set somewhat higher (larger). Without thinning, however, all stands will eventually suffer substantial mortality; prior to that, growth rates will probably decline.

Conclusions

Trends over time (in ways other than rates of development) in bole dimensions, crown size and shape, and stand development may have differed among the species. Irregularities from other causes, however, tended to overshadow any such differences. Cedar and hemlock exhibited more variation than Douglas-fir, and the effects of spacing on the time (age or height) when curves began to separate appeared to be different than for Douglas-fir, but data do not permit a positive statement.

Spacing had little effect on average height to age 25. Heights at the close spacings tended to be a little shorter; but for spacings of 1.8 by 1.8 m and wider there were no clear trends. The wider the spacing: the larger the average d.b.h. of both the total stand and fixed numbers or percentages of larger trees; the greater the bole taper; the less the height to live crown; the greater the crown length, crown ratio, and crown width; the less the competition-related mortality; and the less the basal area and volume production per hectare. Differences in average d.b.h. of the total stand and of fixed numbers of largest trees per hectare generally continued to widen over time.

Results suggest that choice of initial spacing is one of the most important decisions made by a stand manager. In economic and biological terms, the 3.7- and 4.6-m spacings appeared to be near optimum for most regimes involving production of lumber. If combined with pruning, those spacings should also be optimum for producing clear lumber and veneer. The 0.9- and 1.8-m spacings should be considered only if the objective is maximum biomass production without regard to tree size. The 2.7-m spacing can produce high yields where thinning is economically feasible, but the additional wood produced would be expensive.

Establishing stands with wide spacings and with rectangularities up to 2:1 resulted in efficient production of large trees of high value and adequate quality. Spacing trees more widely between rows than within rows (rectangular spacing) can (1) reduce planting and tending costs and (2) facilitate extraction and uniform spacing in the first thinning. When funds are scarce and opportunities for thinning are limited, optimum results can be achieved by planting a given number of trees on more land at wider spacing. If demand for clear wood is expected to continue or increase, then planting at spacings such as 6 by 3 m and pruning to a height of 6 m should produce best results; even close spacings cannot control branch size sufficiently to allow trees to grow clear wood on short rotations without pruning.

Acknowledgments

Most of the UBC trials were established by J. Walters, who recently retired as director of the University of British Columbia Research Forest.

Financial support of the Canadian Forestry Service, 1980-83, made possible the collection of data for age 25 and interpretation of results to age 26. Grants from the Natural Sciences and Engineering Research Council of Canada and the British Columbia Ministry of Forests supported some earlier studies.

Dr. Y. El-Kassaby assembled and summarized data for tables and figures, converted pre-1975 data from imperial units to metric units, and did preliminary plotting and interpretation of results.

Data were collected by various research assistants, graduate and senior students, and University Research Forest staff.

English and Metric Equivalents

1 millimeter (mm) = 0.0394 inch
1 centimeter (cm) = 0.3937 inch
1 meter (m) = 3.281 feet
1 hectare (ha) = 2.471 acres
1 tree per hectare (tree/ha) = 0.4047 tree per acre
1 square meter per hectare (m^2/ha) = 4.356 square feet per acre
1 cubic meter hectare (m^3/ha) = 14.29 cubic feet per acre
1 kilometer (km) = 0.6214 mile
1 °C = (°F-32)/1.8

1 inch (in) = 2.54 centimeters
1 foot (ft) = 0.3048 meter
1 acre (ac) = 0.4047 hectare
1 tree per acre (tree/ac) = 2.471 trees per hectare
1 square foot per acre (ft^2/ac) = 0.2296 square meter per hectare
1 cubic foot per acre (ft^3/ac) = 0.06997 cubic meter per hectare
1 mile (mi) = 1.609 kilometers
1 °F = (9/5 °C) + 32

Literature Cited

Bruce, D. Consistent height-growth and growth-rate estimates for remeasured plots. Forest Science. 27(4): 711-825; **1981.**

Maguire, L.A. A growth model for young conifer stands. In: New forests for a changing world: Proceedings, 1983 National SAF Convention; Portland, OR. Washington, DC: Society of American Foresters; **1984:** 295-299.

Mitchell, K.J.; Cameron, I.R. Managed stand yield tables for coastal Douglas-fir: initial density and precommercial thinning. Land Management Rep. 31. Victoria, BC: British Columbia Ministry of Forests, Research Branch; **1985.** 69 p.

Nelder, J.A. New kind of systematic designs for spacing experiments. Biometrics. Sept: 283-307; **1962.**

Reukema, D.L. Guidelines for precommercial thinning of Douglas-fir. Gen. Tech. Rep. PNW-30. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1975.** 10 p.

Reukema, D.L. Fifty-year development of Douglas-fir stands planted at various spacings. Res. Pap. PNW-253. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1979.** 21 p.

Smith, J.H.G. Comprehensive and economical designs for studies of spacing and thinning. Forest Science. 5(3): 237-252; **1959.**

Smith, J.H.G. Design factors from Nelder and other spacing trials to age 20. Commonwealth Forestry Review 57(2): 109-119; **1978.**

Smith. J.H.G. Graphical summaries and data on the U.B.C. Research Forest spacing trials (57-5) to age 26 and evaluations of results to date. Vancouver, BC: University of British Columbia, Faculty of Forestry; **1983.** 79 p.

Van Tuyll, C; Kramer, H. (The influence of initial spacing on juvenile growth of Douglas-fir. Part II; Investigations in young stands.) Allgemeine Forst und Jagdzeitung. 152(6): 97-102. **1981.**

Walters, J.; Smith, J.H.G. Review of methods used in establishment and summary of early results from spacing trials on U.B.C. Research Forest. Vancouver, BC: University of British Columbia, Faculty of Forestry; **1973.** 40 p.

Appendix

Table 11—Number of trees per hectare, plot size, and number of trees per plot, by trial, plot number, species, and spacing

Trial	Plot number	Species 1/	Spacing	Nominal number of trees per hectare	Plot size	Nominal number of trees per plot
			Meters		Hectare	
49-tree-plot 2/	19	DF	0.9 by 0.9	11,961	0.0082	98
			1.8 by 1.8	2,990	.0164	49
			2.7 by 2.7	1,329	.0369	49
			3.7 by 3.7	748	.0655	49
			4.6 by 4.6	478	.1025	49
	20	WRC	0.9 by 0.9	11,961	.0082	98
			1.8 by 1.8	2,990	.0164	49
			2.7 by 2.7	1,329	.0369	49
			3.7 by 3.7	748	.0655	49
			4.6 by 4.6	478	.1025	49
	21	WH	0.9 by 0.9	11,961	.0082	98
			1.8 by 1.8	2,990	.0164	49
			2.7 by 2.7	1,329	.0369	49
			3.7 by 3.7	748	.0655	49
			4.6 by 4.6	478	.1025	49
0.2-ha plots	15	DF	0.9 by 0.9	11,961	.1977	2,365
	17		1.8 by 1.8	2,990	.2154	644
	14		2.7 by 2.7	1,329	.2144	285
	16		3.7 by 3.7	748	.2406	180
	18		4.6 by 4.6	478	.2510	120
	34	WH	0.9 by 0.9	11,961	.1913	2,288
Rectangularity	46	DF	0.9 by 0.9	11,961	.0326	390
	51		1.4 by 1.4	5,316	.0705	375
	54		1.8 by 1.8	2,990	.1207	361
	47		1.8 by 2.7	1,994	.1906	380
	50		1.8 by 3.7	1,495	.2669	399
	53		2.7 by 2.7	1,329	.2739	364
	52		2.7 by 3.7	997	.2889	288
	49		2.7 by 4.6	797	.4743	378
	48		2.7 by 5.5	665	.5895	392
	62	DF/WH	0.9 by 0.9	11,961	.0522	624
	59		1.4 by 1.4	5,316	.0752	400
	58		1.8 by 1.8	2,990	.1271	380
	60		1.8 by 2.7	1,994	.2287	456
	56		1.8 by 3.7	1,495	.2528	378
	63		2.7 by 2.7	1,329	.3792	504
	57		2.7 by 3.7	997	.3932	392
	61		2.7 by 4.6	797	.3513	280
	55		2.7 by 5.5	665	.5895	392
Nelder	1	DF	Variable	--	.6187	3/ 780
	2	mixed 4/	Variable	--	.6187	816
Variable-block	70	DF	0.9 by 0.9	11,961	.0319	381
	69		1.8 by 1.8	2,990	.1017	304
	65		4.6 by 4.6	478	.3013	144
	68	WH	2.7 by 2.7	1,329	.2814	374
	66		4.6 by 4.6	478	.2259	108
	71	WRC	0.9 by 0.9	11,961	.0402	481
	64		1.8 by 1.8	2,990	.2532	757
	67	SS	1.8 by 1.8	2,990	.1144	342

-- = not applicable.
1/ DF = Douglas-fir, WH = western hemlock, WRC = western redcedar, SS = Sitka spruce.
2/ 2 plots for each spacing. Plots at 0.9-m spacing have 98 trees each.
3/ In Nelder-plot 1, 36 contiguous spokes with 612 trees are used to test variable square spacings, and 12 spokes with 168 trees are used to test rectangular spacings.
4/ In Nelder-plot 2, 4 species (DF, WRC, WH, and SS) are each included successively in groups of 3 spokes. The sequence is repeated 4 times.

Reukema, Donald L.; Smith, J. Harry G. Development over 25 years of Douglas-fir, western hemlock, and western redcedar planted at various spacings on a very good site in British Columbia. Res. Pap. PNW-RP-381. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station; 1987. 46 p.

Results of five spacing trials on the University of British Columbia Research Forest, covering a range of plantation spacings from 1 to 5 meters, showed that choice of initial spacing is among the most important factors influencing bole and crown development and stand growth and yield. The trials include Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western redcedar (*Thuja plicata*). The results to date should help managers to choose optimum spacings for their purposes. Initial wide spacings with rectangularities up to 2:1, such as 6 by 3 meters, resulted in efficient production of large trees of high value and satisfactory quality. Pruning of widely spaced trees to enhance quality of the lower bole is strongly recommended.

Keywords: Plantation spacing, (-growth, stand development, density, height increment, diameter increment, crown development.

The **Forest Service** of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing Nation.

The U.S. Department of Agriculture is an Equal Opportunity Employer. Applicants for all Department programs will be given equal consideration without regard to age, race, color, sex, religion, or national origin.

Pacific Northwest Research Station
319 S.W. Pine St.
P.O. Box 3890
Portland, Oregon 97208

U.S. Department of Agriculture
Pacific Northwest Research Station
319 S.W. Pine Street
P.O. Box 3890
Portland, Oregon 97208

BULK RATE
POSTAGE +
FEES PAID
USDA-FS
PERMIT No. G-40

Official Business
Penalty for Private Use, $300

do NOT detach label

United States
Department of
Agriculture

Forest Service

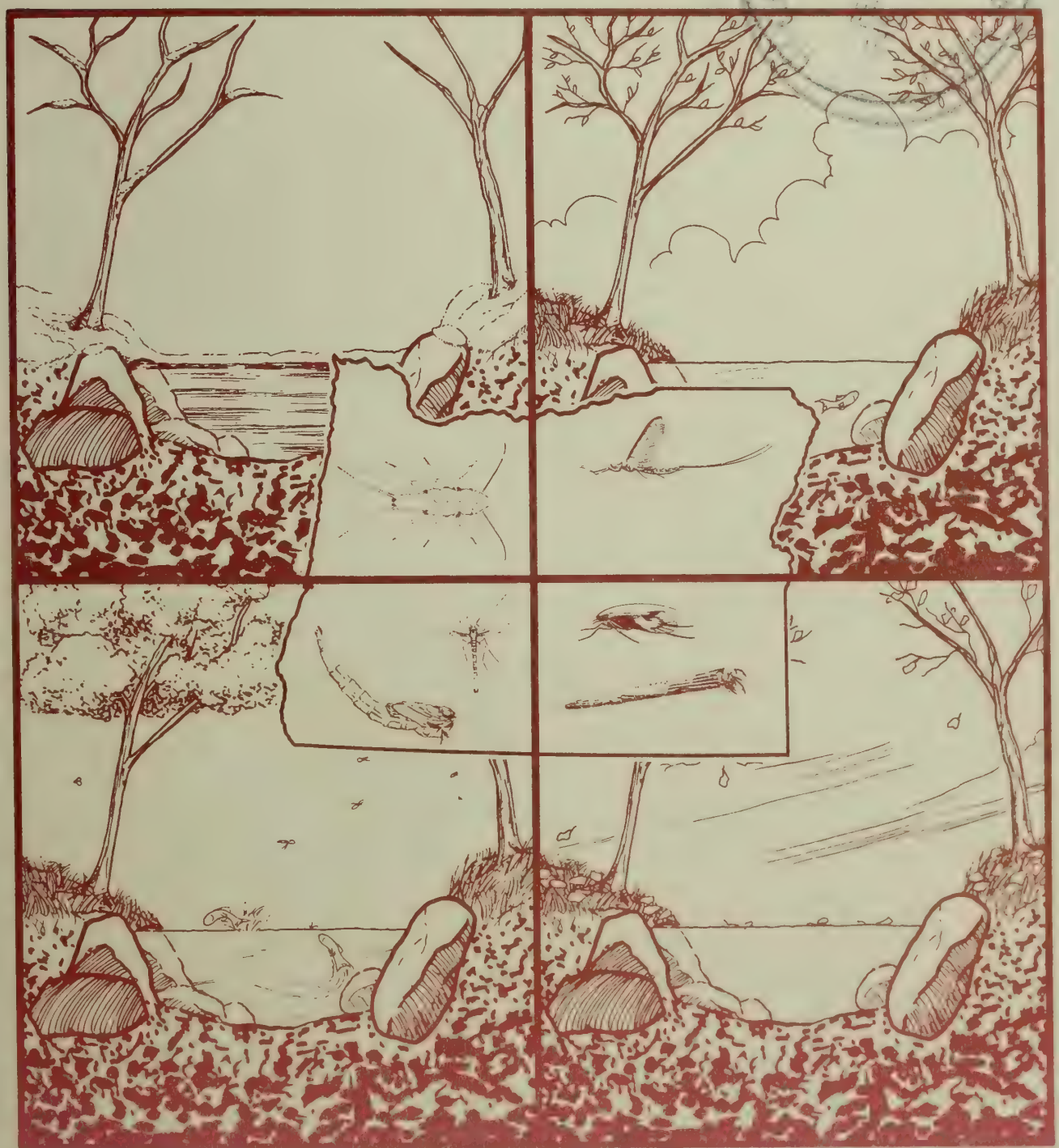
Pacific Northwest
Research Station

Research Paper
PNW-RP-382

Seasonal Composition of Invertebrates in Several Oregon Streams

Pamela E. Porter and William R. Meehan

FEB 2 1988



Authors

PAMELA E. PORTER and WILLIAM R. MEEHAN are research fishery biologists, Forestry Sciences Laboratory, P.O. Box 020909, Juneau, Alaska 99802.

Abstract

Porter, Pamela E.; Meehan, William R. Seasonal species composition of invertebrates in several Oregon streams. Res. Pap. PNW-RP-382. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station; **1987.** 36 p.

The invertebrate communities of eight Oregon streams were sampled seasonally from 1974 to 1976. Benthic, drift, and two types of aerial-trap samples were collected. Occurrence and percentage composition are summarized by sample type, season, and geographic area (coastal, Cascade, central, and eastern Oregon). Within 276 families, 426 taxa were identified; the 20 families most prevalent within each sample type accounted for the majority of organisms collected (77.8-91.8 percent). In most areas and seasons, Diptera and Ephemeroptera together comprised over half of the invertebrates collected.

Keywords: Invertebrata, aquatic life, Oregon.

Summary

During 1974-76, we studied the community structure of invertebrates in streams in the coastal, Cascade, central, and eastern areas of Oregon. Benthic, drift, sticky-trap, and water-trap samples were collected seasonally. Occurrence and percentage composition of invertebrates were summarized by sample type, season, and geographic area.

When data for all sample types were combined, Diptera was the most abundant order collected in summer and fall, and Ephemeroptera were prevalent in winter. In most areas and seasons, combined numbers of Diptera and Ephemeroptera comprised over half of the invertebrates collected.

Within the benthic community, Ephemeroptera and Diptera were the most prevalent orders, although other orders such as Coleoptera and Plecoptera occasionally were quite abundant. Ephemeroptera, Diptera, Plecoptera, and Trichoptera were the dominant orders collected in drift samples. Diptera was the most prevalent order collected in sticky-trap and water-trap samples, except for occasional large numbers of Collembola.

Within 276 families, 426 taxa were collected during the study. When data were summarized by family, the 20 most prevalent families accounted for the majority of organisms collected (77.8-91.8 percent).

Contents

1 **Introduction**
1 **Study Area**
2 **Materials and Methods**
2 Aquatic Sample Types
2 Aerial Sample Types
3 Sampling Schedule
3 Identification of Organisms
4 **Results and Discussion**
6 **English Equivalents**
6 **Literature Cited**
8 **Appendix 1**
8 Presence of Taxa by Season and Area
18 **Appendix 2**
18 Percentage of Samples From Coastal Streams Containing Listed Taxa, by Season and Sample Type
22 Percentage of Samples From Cascade Streams Containing Listed Taxa, by Season and Sample Type
26 Percentage of Samples From Central Streams Containing Listed Taxa, by Season and Sample Type
30 Percentage of Samples From Eastern Streams Containing Listed Taxa, by Season and Sample Type
33 **Appendix 3**
33 Summary of Invertebrate Data for Each Season and Sample Type—Coastal Streams
34 Summary of Invertebrate Data for Each Season and Sample Type—Cascade Streams
35 Summary of Invertebrate Data for Each Season and Sample Type--Central Streams
36 Summary of Invertebrate Data for Each Season and Sample Type—Eastern Streams

Introduction

During 1974-76, we studied the relation of riparian vegetation canopy to the community structure of invertebrates in several streams in Oregon. The composition of invertebrates occurring seasonally in the study streams was evaluated according to several sample types.

The purpose of this report is to provide a list of the invertebrate taxa found in the distinct geographic areas of Oregon in each season. This list will serve as a checklist for other studies of stream ecology in Oregon, and it will be the base of reference for future reports on effects of riparian canopy and food habits.

Study Area

Eight streams in Oregon were selected for study (fig. 1)—two in each of four geographical areas: coastal Oregon, the west side of the Cascade Range, central Oregon, and eastern Oregon. Thus, a general transect of the State from west to east was sampled. All the study streams were second- or third-order streams, comparable in size, and representative of the small streams that furnish a large amount of rearing habitat for young salmon and trout. The study streams, by area, were:

Coastal (tributaries of Five Rivers in the Alsea River drainage):
- Green River
- East Fork Green River

Cascades (tributaries of the Lookout Creek system, which drains into the McKenzie River):
- Mack Creek
- MacRae Creek

Central (tributaries of the Deschutes River drainage):
- Ochoco Creek
- Canyon Creek

Eastern (tributaries of the Grand Ronde River):
- Meadow Creek
- McCoy Creek

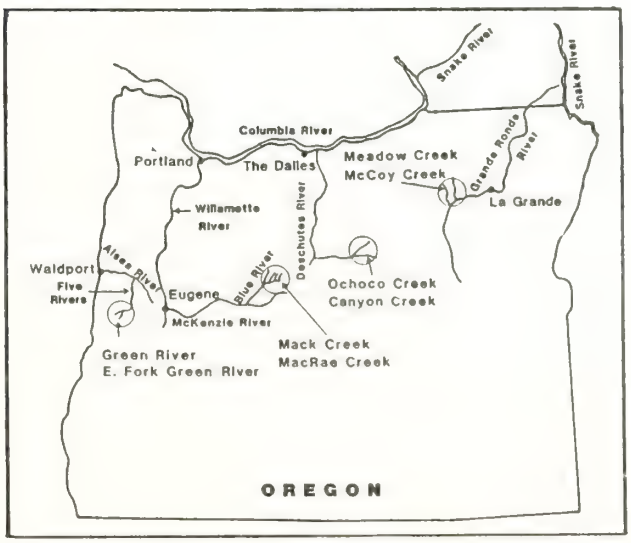


Figure 1—Locations of study streams.

In each of the eight streams, two similar reaches were sampled. Streamside vegetation was a mix of conifers, hardwoods, brush, and grass. Stream substrates were generally similar and ranged from cobble to coarse sand.

Materials and Methods

Aquatic Sample Types

Benthic—Benthic samples were collected with a modified Hess sampler[1/] covering a surface area of 0.09m^2. Two samples were collected from each study reach at the beginning of a 16-day study period and again at the end of the 16 days; the samples were preserved in formal alcohol (half 70-percent ethanol and half 10-percent formalin). In the laboratory, invertebrate organisms were sorted from the samples, counted, and identified to the lowest possible taxonomic level (generally to family and, where feasible, to genus or species). After the invertebrates were sorted, the entire sample was freeze-dried and weighed on an analytical balance to the nearest 0.0001 g.

Drift—Aquatic drift was sampled in each study section with a 280-micrometer mesh Nitex drift net, 76 cm long. Openings in the nets were 0.46 by 0.31 m. One drift net was set in place at the lower end of each study reach for 24 hours at the beginning and end of each 16-day sampling period. Nets were placed in riffles or runs with the bottom of the net on the streambed and the top above the stream surface such that the entire water column was sampled. Samples were processed in the field and laboratory as described above.

Aerial Sample Types

Terrestrial insects and adult aquatic insects that drop into the stream and become part of the drift and potential fish food supply were sampled during each sampling period by means of sticky traps and water traps. A pair (one of each type) was located at each of two sites within each study reach.

Sticky trap—The sticky traps were 0.31-m squares of white-painted 6.35-mm plywood; each was covered with a piece of 6-mil clear polyethylene film. This square surface was sprayed with "Tree Tanglefoot," a sticky substance used as a barrier to crawling insects on trees. Each coated board was taped to a Styrofoam float 0.36 m square and 5.1 cm thick. Two sticky traps were set out in each study reach for the full 16 days of each sampling period. When the trap was removed at the end of the sampling period, the plastic film was cut off at the edges of the board so that a 0.31-m-square collection surface was retained, butcher paper was placed over the sticky side to prevent crushing or mold damage to the specimens, and this film and butcher paper "sandwich" was transported to the laboratory. In the laboratory, the butcher paper was removed and the film cut into 2.54-cm strips for viewing under a microscope. Insects were counted and identified, usually to family.

1/ The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture of any product or service to the exclusion of others that may be suitable.

Water trap—A water trap was made from a 0.33- by 0.28-m plastic dishpan, 0.13 m deep, surrounded by a 0.61- by 0.61-m rectangle of 5.1-cm-thick Styrofoam that supported and floated the pan. The pan was filled to about half its depth with water, and 28.4 g of formalin and 28.4 g of a surfactant (Ortho R X-77 Spreader) were added. The surfactant eliminated surface tension and allowed insects to settle to the bottom. A small hole was bored into a lower corner of the pan and was fitted with a rubber stopper for easy removal of the contents. Two water traps were set out in each study reach for the full 16 days. When a trap was removed at the end of a sampling period, the corner plug was removed and the contents of the pan were strained through a 0.5-mm mesh screen. The material remaining on the screen was washed into a jar with formal alcohol and processed as described for benthic and drift samples.

Sampling Schedule

Each stream was sampled during summer and fall 1974 and during all four seasons in 1975 and 1976. Samples were taken at the following times: winter—mid January to early February; spring—early April to late April; summer—early July to late July; and fall—early October to early November.

A sampling period was organized as follows: On day 1, sticky traps, water traps, and drift nets were set out. On day 2, 24 hours later, drift nets were pulled. During these 2 days, benthic samples were taken.

Two weeks later, another sampling trip was made. On Day 15, drift nets were set out, and 24 hours later (day 16), they were pulled. Sticky traps and water traps that had been in place during the 16-day period were removed. During these 2 days, benthic samples were again taken.

Because of ice and other weather-related problems, the winter sampling period at the central and eastern sites in both years, and at the Cascade site in 1976, was only one trip of 2 days rather than two trips over 16 days. During these shortened sampling periods, samples from sticky traps and water traps were not obtained, and only half as many of the other samples were collected. We had planned to collect the following samples during the entire study: benthic, 600; drift, 300; and sticky trap and water trap, 280 each. But actual numbers of samples were fewer because on a few occasions sampling gear malfunctioned or was lost.

Identification of Organisms

We used several sources to identify the organisms collected. Invertebrates other than insects were identified through descriptions in Pennak (1978), Ward and Whipple (1959), and Burch (1982). Aquatic insects were identified from taxonomic keys in Hatch (1953, 1957, 1961, 1965, 1971), Usinger (1956), Jensen (1966), Cole (1969), Anderson (1976), Edmunds and others (1976), Baumann and others (1977), and Merritt and Cummins (1978). Terrestrial insects were identified primarily from Borror and others (1976). Amphibians and fish were identified from Stebbins (1954) and Bond (1973), respectively.

Results and Discussion

Table 1 and figure 2 show the percentage composition by season of the major orders of invertebrates collected in each of the four study areas. In all areas, Diptera was the most abundant order collected in the summer and fall, and mayflies (Ephemeroptera) were prevalent in the winter. In all areas other than central Oregon, spring samples also contained high percentages of mayflies, although springtails (Collembola) dominated the spring samples in central Oregon and stoneflies (Plecoptera) were prevalent in eastern Oregon. In most areas and seasons, Diptera and Ephemeroptera combined comprised over half of the invertebrates collected.

Table 1—Number and percentage composition of invertebrates, by order, for each season and geographic area

Area and order	Winter		Spring		Summer		Fall		All seasons	
	No.	*Percent*	*No.*	*Percent*	*No.*	*Percent*	*No.*	*Percent*	*No.*	*Percent*
Coastal:										
Gastropoda	51	(1.8)	207	(1.7)	1,052	(4.6)	615	(4.8)	1,925	(3.8)
Collembola	28	(1.0)	477	(3.9)	85	(.4)	192	(1.5)	782	(1.5)
Ephemeroptera	1,293	(46.6)	5,571	(45.1)	2,479	(10.9)	1,819	(14.1)	11,162	(21.9)
Plecoptera	231	(8.3)	1,158	(9.4)	1,586	(6.9)	1,567	(12.1)	4,542	(8.9)
Hemiptera	6	(.2)	85	(.7)	233	(1.0)	51	(.4)	375	(.7)
Homoptera	5	(.2)	32	(.3)	241	(1.1)	117	(.9)	395	(.8)
Coleoptera	70	(2.5)	1,149	(9.3)	2,517	(11.0)	2,575	(19.9)	6,311	(12.4)
Trichoptera	221	(8.0)	676	(5.5)	995	(4.4)	1,550	(12.0)	3,442	(6.8)
Diptera	832	(30.0)	2,777	(22.5)	13,149	(57.6)	4,108	(31.8)	20,866	(41.0)
Other [1]	35	(1.3)	230	(1.9)	501	(2.2)	330	(2.6)	1,096	(2.2)
Total	2,772		12,362		22,838		12,924		50,896	
Cascade:										
Oligochaeta	39	(.8)	231	(1.4)	132	(.5)	183	(1.5)	585	(1.0)
Collembola	574	(12.1)	564	(3.4)	3,031	(11.1)	2,333	(18.8)	6,502	(10.6)
Ephemeroptera	1,734	(36.6)	9,413	(56.0)	4,762	(17.4)	2,063	(16.6)	17,972	(29.3)
Plecoptera	1,327	(28.0)	2,327	(13.8)	1,298	(4.8)	2,250	(18.1)	7,202	(11.8)
Coleoptera	28	(.6)	89	(.5)	832	(3.0)	364	(2.9)	1,313	(2.1)
Trichoptera	564	(11.9)	607	(3.6)	1,311	(4.8)	709	(5.7)	3,191	(5.2)
Diptera	414	(8.7)	3,478	(20.7)	14,563	(53.4)	4,022	(32.4)	22,477	(36.7)
Other	52	(1.1)	104	(.6)	1,367	(5.0)	506	(4.1)	2,029	(3.3)
Total	4,732		16,813		27,296		12,430		61,271	
Central:										
Collembola			14,054	(49.1)	9,046	(24.1)	3,063	(10.0)	26,163	(25.3)
Ephemeroptera	2,076	(32.3)	3,444	(12.0)	4,816	(12.8)	7,464	(24.3)	17,800	(17.2)
Plecoptera	1,865	(29.0)	3,585	(12.5)	922	(2.5)	2,699	(8.8)	9,071	(8.8)
Homoptera			69	(.2)	1,969	(5.2)	1,375	(4.5)	3,413	(3.3)
Coleoptera	205	(3.2)	362	(1.3)	2,269	(6.0)	2,699	(8.8)	5,535	(5.4)
Trichoptera	345	(5.4)	1,192	(4.2)	2,071	(5.5)	2,810	(9.1)	6,418	(6.2)
Diptera	1,873	(29.1)	5,657	(19.8)	14,839	(39.5)	9,777	(31.8)	32,146	(31.1)
Hymenoptera			19	(.1)	586	(1.6)	217	(.7)	822	(.8)
Other	71	(1.1)	242	(.8)	1,040	(2.8)	670	(2.2)	2,023	(2.0)
Total	6,435		28,624		37,558		30,774		103,391	
Eastern										
Oligochaeta	34	(1.9)	148	(1.8)	28	(.1)	554	(2.2)	764	(1.3)
Gastropoda	19	(1.1)	9	(.1)	34	(.2)	581	(2.3)	643	(1.1)
Araneae			8	(.1)	272	(1.3)	152	(.6)	432	(.8)
Collembola	2	(.1)	442	(5.4)	12	(.1)	245	(1.0)	701	(1.2)
Ephemeroptera	569	(31.5)	563	(6.9)	3,705	(17.2)	5,063	(19.7)	9,900	(17.3)
Plecoptera	446	(24.7)	3,984	(49.0)	1,099	(5.1)	1,342	(5.2)	6,871	(12.0)
Hemiptera	10	(.6)	3	(.0)	211	(1.0)	180	(.7)	404	(.7)
Homoptera	1	(.1)	21	(.3)	1,002	(4.7)	5,426	(21.1)	6,450	(11.3)
Coleoptera	130	(7.2)	128	(1.6)	1,434	(6.7)	1,587	(6.2)	3,279	(5.7)
Trichoptera	124	(6.9)	130	(1.6)	818	(3.8)	1,751	(6.8)	2,823	(4.9)
Diptera	439	(24.3)	2,657	(32.7)	12,350	(57.5)	8,224	(32.0)	23,670	(41.4)
Hymenoptera	1	(.1)	4	(.0)	229	(1.1)	138	(.5)	372	(.7)
Other	30	(1.7)	34	(.4)	287	(1.3)	492	(1.9)	843	(1.5)
Total	1,805		8,131		21,481		25,735		57,152	

[1] Other is the total of all orders having a percentage composition less than 1.0 in any season.

Within 276 families, 426 taxa were collected (appendix 1); the 20 most prevalent families within each sample type accounted for the majority of organisms collected (benthos 89.2 percent, drift 80.4 percent, sticky trap 91.8 percent, water trap 77.8 percent—see table 2). Appendix 2 lists the frequency of occurrence, by family, of organisms collected during the study.

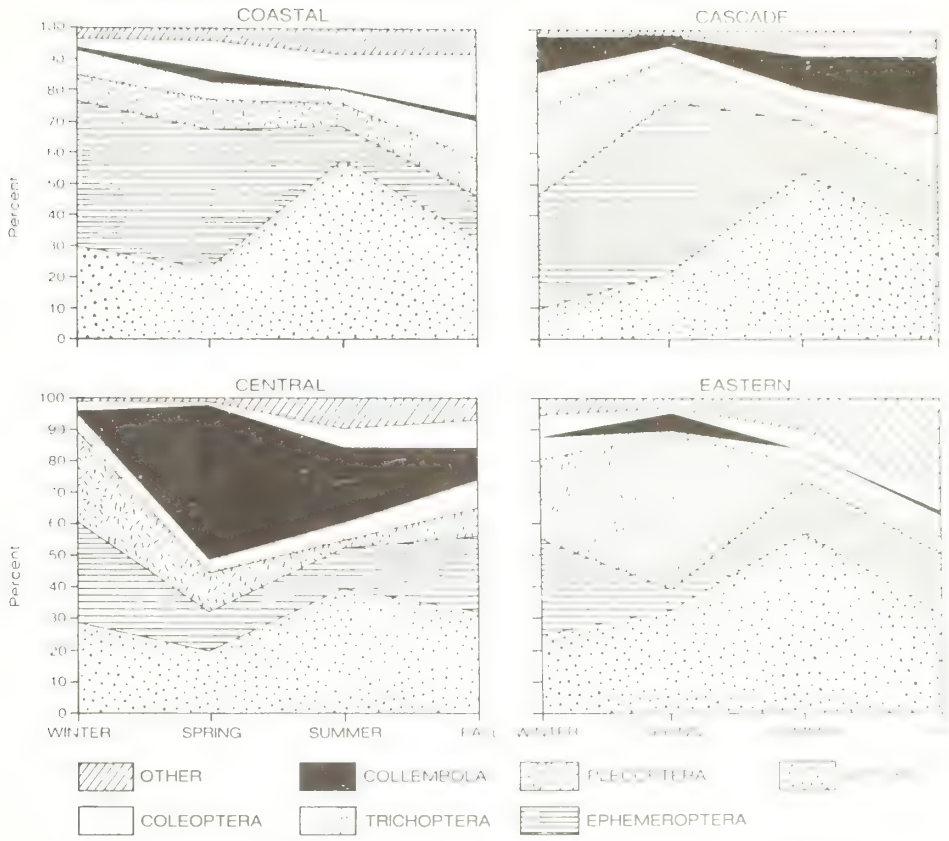


Figure 2—Percentage composition of major orders of invertebrates, by season, for coastal, Cascade, central, and eastern streams in Oregon.

Table 2—Percentage composition of the 20 most prevalent families [1] collected, by sample type

Benthic		Drift		Sticky trap		Water trap	
Taxa	Percent	Taxa	Percent	Taxa	Percent	Taxa	Percent
[illegible]	14.4	Baetidae	16.2	Chironomidae	19.0	Chironomidae	[illegible]
Heptageniidae	13.7	Chironomidae	15.4	Dolichopodidae	12.9	[illegible]	[illegible]
[illegible]	10.5	Nemouridae	7.2	Collembola	9.7	[illegible]	[illegible]
Baetidae	[illegible]	Heptageniidae	5.3	Empididae	9.2	[illegible]	[illegible]
Chloroperlidae	6.4	Ephemerellidae	4.2	Muscoidea	7.7	Ephydridae	[illegible]
Ephemerellidae	6.4	Limnephilidae	4.1	Cicadellidae	[illegible]	[illegible]	4.2
Tipulidae	4.0	Pleuroceridae	3.7	Trichoptera	4.1	Sciaridae	[illegible]
Leptophlebiidae	3.8	[illegible]	3.0	Isotomidae	3.6	Tipulidae	[illegible]
Nemouridae	3.3	Capniidae	2.8	Mycetophilidae	2.5	Dolichopodidae	[illegible]
Perlidae	2.8	Siphlonuridae	2.3	Nemouridae	[illegible]	Nemouridae	[illegible]
Oligochaeta	2.5	Cicadellidae	2.3	Diptera	2.6	Araneae	[illegible]
[illegible]	2.4	Elmidae	2.3	Tipulidae	2.0	[illegible]	[illegible]
[illegible]	2.2	Leptophlebiidae	1.9	Sciaridae	1.9	[illegible]	[illegible]
Siphlonuridae	2.0	Sciaridae	[illegible]	Ephemeroptera	1.9	[illegible]	[illegible]
[illegible]	[illegible]	Amnicolidae	1.6	Platypezidae	[illegible]	[illegible]	[illegible]
Perlodidae	1.4	Calamoceratidae	1.2	Staphylinidae	1.3	Cicadellidae	[illegible]
Hydropsychidae	[illegible]	Chloroperlidae	1.2	Plecoptera	[illegible]	Capniidae	[illegible]
[illegible]	1.3	Ephemeroptera	1.0	Araneae	[illegible]	[illegible]	[illegible]
[illegible]	1.2	Psychodidae	[illegible]	Ephydridae	[illegible]	[illegible]	[illegible]
Pleuroceridae	[illegible]	Aphididae	[illegible]	Chloroperlidae	[illegible]	[illegible]	[illegible]
Total	89.2		79.4		91.8		77.6

[1] A few higher taxa are included where identification could not be made to the family level.

When the data are divided by sample type, seasonal and geographic trends become apparent (appendix 3). Within the benthic community, Diptera were more prevalent in summer and fall than in winter or spring in Cascade streams, while in coastal streams they were more prevalent in fall; in central and eastern streams, Diptera were dominant in spring samples. Within the drift, Diptera showed no obvious trend across season or geographic area. Diptera was also the most prevalent order collected in sticky-trap and water-trap samples except for occasional large numbers of Collembola. Ephemeroptera within the benthos were most common during winter and spring sampling; within the drift, their presence peaked during spring and summer sample periods in all areas except eastern Oregon, where they were most numerous in the winter samples. Adult mayflies were never abundant in sticky-trap or water-trap samples. Plecoptera were an important component of winter and spring drift samples collected in eastern Oregon; adult stoneflies also dominated spring water-trap samples in this area. Collembola were occasionally important in all areas except coastal Oregon, but particularly in central Oregon where they comprised over 25 percent of all organisms collected. Collembola were found primarily in sticky-trap and water-trap samples and generally during spring and fall.

English Equivalents

1 meter (m) = 3.28 feet
1 square meter (m^2) = 10.76 square feet
1 centimeter (cm) = 0.39 inch
1 millimeter (mm) = 0.039 inch
1 micrometer (μ) = 0.000039 inch
1 gram (g) = 0.035 ounce

Literature Cited

Anderson, Norman H. The distribution and biology of the Oregon Trichoptera. Tech. Bull. 134. Corvallis, OR: Oregon State University, Agricultural Experiment Station; **1976.** 152 p.

Baumann, Richard W.; Gaufin, Arden R.; Surdick, Rebecca F. The stoneflies (Plecoptera) of the Rocky Mountains. Memoirs of the American Entomological Society. 31: 1-208; **1977.**

Bond, Carl E. Keys to Oregon freshwater fishes. Tech. Bull. 58. Corvallis, OR: Oregon State University, Agricultural Experiment Station; **1973.** 42 p.

Borror, Donald J.; Delong, Dwight M.; Triplehorn, Charles A. An introduction to the study of insects. 4th ed. New York, NY: Holt, Rinehart and Winston; **1976.** 852 p.

Burch, J.B. Freshwater snails (Mollusca: Gastropoda) of North America. EPA-600/3-82-026. Cincinnati, OH: U.S. Environmental Protection Agency; **1982.** 294 p.

Cole, Frank R. The flies of western North America. Berkeley, CA: University of California Press; **1969.** 693 p.

Edmunds, George F., Jr.; Jensen, Steven L.; Berner, Lewis. The mayflies of North and Central America. Minneapolis, MN: University of Minnesota Press; **1976.** 330 p.

Hatch, Melville H. The beetles of the Pacific Northwest. Part I: Introduction and Adephaga. Seattle, WA: University of Washington Press; **1953.** 340 p.

Hatch, Melville H. The beetles of the Pacific Northwest. Part II: Staphyliniformia. Seattle, WA: University of Washington Press; **1957.** 384 p.

Hatch, Melville H. The beetles of the Pacific Northwest. Part III: Pselaphidae and Diversicornia I. Seattle, WA: University of Washington Press; **1961.** 503 p.

Hatch, Melville H. The beetles of the Pacific Northwest. Part IV: Macrodactyles, Palpicornes and Heteromera. Seattle, WA: University of Washington Press; **1965.** 268 p.

Hatch, Melville H. The beetles of the Pacific Northwest. Part V: Rhipiceroidea, Sternoxi, Phytophaga, Rhynchophora and Lamellicornia. Seattle, WA: University of Washington Press; **1971.** 662 p.

Jensen, Stephen Leroy. The mayflies of Idaho (Ephemeroptera). Salt Lake City, UT: University of Utah; **1966.** 352 p. M.S. thesis.

Merritt, Richard W.; Cummins, Kenneth W., eds. An introduction to the aquatic insects of North America. Dubuque, IA: Kendall/Hunt Publishing Co.; **1978.** 411 p.

Pennak, Robert W. Fresh-water invertebrates of the United States. 2d ed. New York, NY: John Wiley and Sons; **1978.** 803 p.

Stebbins, Robert C. Amphibians and reptiles of western North America. New York, NY: McGraw-Hill Book Co.; **1954.** 528 p.

Usinger, Robert L., ed. Aquatic insects of California. Berkeley, CA: University of California Press; **1956.** 508 p.

Ward, Henry Baldwin; Whipple, George Chandler. Fresh-water biology 2d ed. New York, NY: John Wiley and Sons; **1959.** 1248 p.

Appendix 1

Presence of Taxa by Season and Area

Individuals were identified to the lowest taxonomic level. Presence was recorded at this level and not entered at the broader taxonomic levels.

	Coastal				Cascade				Central				Eastern			
Taxa	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Platyhelminthes																
Turbellaria																
Tricladida																
Planariidae	x				x	x	x	x	x	x	x	x	x	x	x	x
Nematomorpha							x									
Nematoda	x		x	x	x	x	x	x		x	x	x			x	x
Annelida																
Oligochaeta	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Hirudinea	x		x	x												
Mollusca																
Gastropoda	x	x	x	x	x	x					x					x
Basommatophora																
Lymnaeidae																
Lymnaea				x												
Physidae																
Physa												x	x	x	x	x
Planorbidae				x												
Helisoma											x	x				x
Ancylidae																
Ferrissia													x	x		x
Stylommatophora	x			x												
Mesogastropoda																
Hydrobiidae				x												
Fluminicola	x	x	x	x						x	x	x	x		x	
Pleuroceridae	x	x	x	x											x	
Juga	x	x	x	x											x	
Pelecypoda										x						
Margaritiferidae															x	
Sphaeriidae			x	x					x			x	x	x	x	x
Unionidae															x	
Arthropoda																
Crustacea																
Decapoda																
Astacidae																
Astacus (Pacifastacus)			x	x											x	x
A. klamathensis															x	x
A. leniusculus			x	x									x		x	x
A. trowbridgi		x	x	x									x	x	x	x
Amphipoda								x		x	x	x		x		x
Isopoda	x	x		x												
Ostracoda					x			x				x				x
Copepoda				x								x				x
Arachnida																
Araneae	x	x	x	x	x	x	x	x		x	x	x		x	x	x
Acarina	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Pseudoscorpionida											x					
Opiliones		x	x	x			x	x				x			x	

Table continued on next page

Taxa	Coastal				Cascade				Central				Eastern			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Insecta				x			x	x		x	x				x	
Thysanura																
Machilidae		x						x			x					
Collembola	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x
Sminthuridae	x	x	x	x		x		x		x		x		x		
Poduridae				x			x									
Isotomidae	x	x	x	x	x	x	x	x		x	x	x		x		x
Ephemeroptera	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x
Siphlonuridae	x							x							x	
Siphlonurus							x								x	
Ameletus	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Baetidae			x				x				x				x	
Baetis	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
B. bicaudatus	x	x	x	x	x	x	x	x					x	x	x	x
B. hageni		x		x				x								
B. tricaudatus	x	x	x	x	x		x	x					x	x	x	x
Centroptilum						x		x			x				x	
Heptageniidae	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x
Epeorus	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
E. sg. *Ironopsis*					x	x	x	x								
E. longimanus		x		x		x	x	x						x		
E. albertae			x													
E. deceptivus						x										
Ironodes						x										
I. nitidus		x			x	x	x	x								
Cinygmula	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Cinygma	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Rhithrogena	x	x	x	x	x	x	x	x	x	x	x	x			x	x
R. hageni								x								
R. robusta				x	x	x		x								
Stenonema			x		x		x				x				x	
Leptophlebiidae				x			x				x			x	x	
Paraleptophlebia	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
P. bicornuta				x												x
P. heteronea			x	x		x									x	x
P. debilis		x		x		x									x	
P. temporalis		x		x	x	x	x	x					x	x	x	x
Leptophlebia													x			x
Ephemerellidae		x					x				x				x	
Ephemerella	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
E. sg. *Caudatella*						x										
E. sg. *Drunella*	x	x	x	x		x	x	x								x
E. aurivilli	x															
E. doddsi		x		x	x	x	x	x								
E. edmundsi	x															
E. flavilinea		x				x										
E. grandis						x	x									x
E. infrequens		x		x	x	x	x	x					x	x		x
E. spinifera				x	x	x	x	x								
E. tibialis							x								x	
E. hecuba		x	x	x			x	x							x	x
E. margarita															x	x
E. terea		x					x								x	
E. coloradensis				x		x	x									
E. jacobi		x			x	x	x	x								
E. pelosa						x										
Odonata																

Table continued on next page

Taxa	Coastal				Cascade				Central				Eastern			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Anisoptera			x				x								x	
Aeshnidae																x
Anax																x
Gomphidae			x								x					
Ophiogomphus																x
Cordulegastridae									x			x				
Libellulidae										x						
Coenagrionidae																
Argia			x												x	
Orthoptera		x									x				x	x
Tetrigidae										x		x				
Gryllidae											x				x	
Phaneropterinae				x												
Gryllacrididae		x	x	x		x	x	x								
Acrididae							x	x							x	
Dermaptera			x													
Forficulidae												x				
Plecoptera	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x
Pteronarcidae		x	x				x									
Pteronarcella			x	x				x								
Pteronarcys			x	x		x	x	x					x			
Peltoperlidae																
Yoraperla			x	x	x	x	x	x	x	x	x	x				
Taeniopterygidae																
Brachypteriginae	x	x	x	x	x	x	x	x			x	x		x		x
Nemouridae	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Zapada	x	x	x	x	x	x	x	x					x		x	x
Malenka		x		x	x	x	x	x					x	x	x	x
Capniidae	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Capnia				x	x	x	x	x		x			x	x	x	x
Isocapnia						x										
Eucapnopsis	x		x		x	x			x			x		x		
Leuctridae	x	x	x	x	x	x	x	x	x	x		x		x		
Despaxia																
D. augustus					x	x		x								
Perlidae	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Calineuria																
C. californica	x	x	x	x	x	x	x	x					x	x	x	x
Claassenia		x	x						x	x	x	x				
Hesperoperla	x	x	x	x				x								
Perlodidae	x	x	x	x		x	x	x			x		x		x	x
Perlodinae	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Isoperla	x	x	x	x		x		x	x	x	x	x		x	x	
Perlinodes																
P. aurea													x			x
Skwala				x	x	x	x	x								x
Chloroperlidae	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
Chloroperlinae	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Hastaperla			x													

Table continued on next page

Taxa	Coastal				Cascade				Central				Eastern			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Paraperlinae																
Paraperla		x	x	x			x									
Kathroperla					x		x	x								
Psocoptera			x	x			x	x			x	x			x	x
Mallophaga			x				x	x								
Thysanoptera		x	x	x			x			x	x	x			x	x
Hemiptera		x	x	x	x		x	x		x	x	x	x		x	
Corixidae									x		x	x	x		x	x
Graptocorixa																x
Hesperocorixa													x			x
Trichocorixa																x
Neididae											x					
Macroveliidae																
Macrovelia				x												
Gerridae		x	x	x			x	x		x	x	x			x	x
Gerris	x	x	x	x		x	x	x		x	x			x	x	x
Trepobates			x								x				x	x
Veliidae		x	x	x							x	x				
Microvelia		x	x	x												
Mesoveliidae		x														
Saldidae		x	x				x	x			x	x			x	x
Anthocoridae											x				x	
Miridae		x	x	x			x	x			x	x			x	
Nabidae							x				x				x	x
Reduviidae											x	x				x
Tingidae		x	x	x			x				x					
Aradidae			x								x					
Coreidae							x									x
Lygaeidae		x	x	x			x				x				x	
Pentatomidae			x	x												
Homoptera	x	x	x	x			x	x		x	x	x		x	x	x
Cicadellidae	x	x	x	x		x	x	x		x	x	x	x	x	x	x
Cercopidae			x	x			x	x		x	x	x		x	x	x
Delphacidae						x	x				x				x	
Achilidae							x									
Psyllidae		x	x	x		x	x	x		x	x	x		x		x
Aphididae	x	x	x	x			x	x		x	x	x		x	x	x
Eriosomatidae			x								x	x				x
Chermidae				x												
Coccoidea		x		x						x		x				
Coleoptera	x	x	x	x	x		x	x		x	x	x	x	x	x	x
Cupedidae											x					
Silphidae											x					
Lathridiidae		x		x			x				x					
Noteridae							x	x								
Pronoterus															x	
Carabidae		x	x	x			x			x	x	x			x	x
Haliplidae											x	x			x	x
Brychius													x		x	x
Amphizoidae			x	x	x		x	x			x	x				
Dytiscidae	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x
Deronectes		x	x											x		x
Oreodytes		x	x				x				x				x	

Table continued on next page

Taxa	Coastal				Cascade				Central				Eastern			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Agabus		x													x	
Bidessus															x	x
Hydroporinae							x									
Hydroporus								x							x	
Hydrovatus		x	x	x			x	x					x		x	x
Melyridae			x			x										
Gyrinidae	x											x				
Histeridae			x				x								x	x
Hydrophilidae		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Paracymus			x				x									
Crenitis		x	x				x				x				x	
Laccobius				x			x			x	x	x		x	x	
Ametor				x		x	x				x					
Berosus											x				x	
Tropisternus											x					
Helophorus				x	x	x								x	x	x
Hydrobius							x									
Hydraenidae (Limnebiidae)		x			x	x	x	x	x	x	x	x	x	x	x	x
Hydraena		x						x		x	x	x	x	x	x	x
Ochthebius			x		x							x	x	x	x	x
Melandryidae							x				x				x	
Scarabaeidae							x				x				x	
Cicindelidae							x									
Ptiliidae		x	x	x			x				x	x			x	x
Chrysomelidae	x	x	x	x			x	x		x	x	x			x	x
Scaphidiidae											x	x				
Staphylinidae	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x
Pselaphidae							x									
Colydiidae			x	x							x					
Scydmaenidae												x			x	
Meloidae							x									
Cantharidae		x	x				x				x				x	
Lampyridae							x								x	
Curculionidae (Nemonychidae)		x	x	x			x	x		x	x	x				x
Malachiidae											x					
Cleridae							x			x	x	x				
Elateridae			x	x	x		x				x				x	
Eucnemidae							x									
Byrrhidae	x			x												
Buprestidae							x				x	x				
Dascillidae			x				x									
Ptilodactylidae						x										
Helodidae						x						x				
Dryopidae											x	x				
Limnichidae							x									
Psephenidae							x									x
Acneus																
A. quadrimaculatus							x									
Elmidae	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Heterlimnius	x	x	x	x		x	x	x			x	x			x	
Optioservus	x	x	x	x		x	x	x					x	x	x	x

Table continued on next page

Taxa	Coastal				Cascade				Central				Eastern			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Heterlimnius-optioservus		x	x	x				x			x				x	x
Narpus			x	x		x		x			x					
N. concolor							x									
Zaitzevia		x	x								x		x		x	x
Lara	x	x	x	x	x	x	x	x			x					x
Microcylloepus											x	x				
Cleptelmis								x			x	x	x			x
Dubiraphia												x				
Ordobrevia															x	x
Ampumixis																x
Scolytidae		x	x				x				x	x		x	x	x
Derodontidae							x	x			x	x				
Cryptophagidae		x					x									
Bostrichidae							x								x	
Nitidulidae		x	x				x	x		x	x	x			x	
Cucujidae							x									
Endomychidae	x						x									
Coccinellidae			x	x			x				x				x	x
Cerambycidae		x					x				x				x	
Anthicidae			x				x									
Pedilidae												x				
Cephaloidae											x					
Mordellidae							x				x					
Tenebrionidae							x				x					
Neuroptera		x				x		x				x			x	
Megaloptera																
Sialidae																
Sialis			x	x	x		x	x		x			x	x	x	x
Corydalidae					x	x	x	x								
Dysmicohermes			x		x	x	x									
Raphidioptera																
Raphidiidae											x					
Planipennia																
Coniopterygidae											x					
Hemerobiidae			x			x						x				
Chrysopidae						x	x								x	
Trichoptera	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x
Limnephilidae	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Neophylax	x	x	x	x	x	x	x	x	x	x	x	x			x	x
Hesperophylax			x						x	x	x	x	x	x		x
Apatania			x	x		x		x	x	x		x			x	
Dicosmoecus		x	x				x				x	x	x		x	x
Ecclisomyia	x	x	x		x	x	x	x	x	x	x	x		x	x	
Lenarchus			x							x	x					
Chryanda	x															
Onocosmoecus	x	x	x	x	x	x	x		x	x	x	x			x	x
Clostoeca								x								
Goera	x	x	x	x												
Hydatophylax	x							x								
Cryptochia	x						x	x				x				
Psychoglypha									x			x				
Neothremma					x		x									

Table continued on next page

Taxa	Coastal				Cascade				Central				Eastern			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Limnephilus						x			x							
Grammotaulius											x	x				
Philopotamidae		x	x	x	x	x	x	x			x	x	x		x	x
Wormaldia	x	x	x	x		x	x				x				x	
Dolophilodes						x	x									
Rhyacophilidae	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Rhyacophila	x	x	x	x	x	x	x	x	x		x	x	x	x	x	
R. acropedes				x	x	x	x	x								
R. angelita		x				x								x		
R. tucula							x									
R. blarina				x	x		x									
R. narvae					x	x	x	x								
R. vaefes					x	x	x	x						x		
R. betteni group				x		x	x	x								
R. verrula		x			x	x	x									
R. arnaudi				x												
Himalopsyche								x								
H. phryganea																x
Hydropsychidae	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Hydropsyche		x	x	x					x	x	x	x	x	x	x	x
Arctopsyche			x	x	x	x	x	x	x	x	x	x				x
Parapsyche		x	x	x	x	x	x	x	x	x	x	x				
Homoplectra					x											
Cheumatopsyche	x	x		x									x	x	x	x
Psychomyiidae					x	x	x				x	x				
Psychomyia		x	x	x	x										x	x
Polycentropodidae			x		x	x	x	x		x		x			x	
Polycentropus			x			x	x	x								
Brachycentridae	x	x	x	x	x	x	x	x	x	x	x	x				
Micrasema	x	x		x	x	x	x	x	x	x	x	x				
Calamoceratidae						x										
Heteroplectron				x				x								
Lepidostomatidae																
Lepidostoma	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Glossosomatidae	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Anagapetus	x		x		x	x		x			x	x				x
Agapetus					x						x	x			x	
Glossosoma	x	x	x	x		x	x					x	x			x
Phryganeidae			x				x					x				
Hydroptilidae	x		x	x			x	x							x	x
Hydroptila													x		x	x
Palaeagapetus							x									
Ochrotrichia								x								
Leptoceridae															x	
Lepidoptera		x	x	x		x	x	x		x	x	x		x	x	x
Pieridae							x									
Lycaenidae				x			x									
Satyridae				x								x				x
Hesperiidae				x			x					x				x
Arctiidae											x	x				
Noctuidae										x	x	x			x	x
Geometridae		x	x	x			x	x			x	x			x	
Microlepidoptera		x	x				x			x	x	x			x	x
Pyralidae				x			x							x		x

Table continued on next page.

Taxa	Coastal				Cascade				Central				Eastern			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Aegeriidae (Sesiidae)							x									
Diptera	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x
Nematocera	x	x		x	x			x		x	x	x		x	x	x
Tanyderidae		x		x			x	x								
Tipulidae	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Limoniinae														x		
Antocha	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Limnophila		x	x		x	x	x				x			x	x	
Dicranota	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Tipula			x		x			x								x
Hexatoma	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Hesperoconopa	x	x	x	x	x			x	x						x	
Molophilus	x	x	x	x												
Psychodidae	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Psychoda													x			
Pericoma		x		x	x					x						x
Maruina							x								x	
Ptychopteridae	x	x		x												
Blephariceridae					x	x	x			x	x	x		x		x
Deuterophlebiidae						x										
Dixidae	x	x	x	x	x	x	x	x		x	x	x		x	x	x
Meringodixa				x			x				x				x	x
Dixa		x	x	x			x	x			x				x	x
Culicidae		x		x			x					x				
Ceratopogonidae	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x
Forcipomyia							x	x								
Bezzia			x													
Chironomidae	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Simuliidae	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Bibionidae		x				x						x				x
Mycetophilidae	x	x	x	x	x	x	x	x		x	x	x		x	x	x
Sciaridae	x	x	x	x		x	x	x		x	x	x		x	x	x
Cecidomyiidae		x	x	x			x	x		x	x	x		x	x	x
Brachycera																x
Xylomyidae											x					
Stratiomyidae				x				x	x		x	x		x		
Tabanidae	x		x				x		x	x	x	x	x	x	x	x
Rhagionidae		x	x				x				x				x	
Therevidae			x								x	x				
Periscelididae							x								x	
Asilidae		x	x				x				x	x			x	
Acroceridae			x				x				x				x	
Bombyliidae							x								x	
Empididae	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x
Dolichopodidae	x	x	x	x	x	x	x	x		x	x	x		x	x	x
Cyclorrhapha											x				x	x
Lonchopteridae			x	x			x				x	x			x	x
Phoridae	x	x	x	x	x	x	x	x		x	x	x		x	x	x
Pipunculidae			x	x			x				x	x				
Syrphidae		x	x	x			x	x			x	x			x	
Conopidae							x									

Table continued on next page.

Taxa	Coastal				Cascade				Central				Eastern			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Sepsidae							x			x	x	x				
Sciomyzidae				x			x								x	
Lauxaniidae			x			x	x								x	
Lonchaeidae		x				x				x				x		
Sphaeroceridae	x	x	x	x			x	x		x		x		x	x	
Milichiidae			x				x								x	x
Tephritidae		x					x	x								
Ephydridae	x	x	x	x	x	x	x	x		x	x	x		x	x	x
Drosophilidae		x	x	x		x	x	x			x	x			x	x
Chloropidae		x	x	x		x	x				x	x			x	
Agromyzidae		x	x	x			x				x	x			x	x
Clusiidae	x	x	x												x	
Heleomyzidae			x			x						x			x	x
Anthomyzidae			x								x				x	
Anthomyiidae (Scatophagidae)		x	x	x			x	x		x	x	x		x	x	x
Muscoidea	x	x	x	x	x	x	x	x		x	x	x		x	x	x
Muscidae		x	x	x		x	x	x			x	x		x	x	x
Oestroidea											x					
Calliphoridae			x			x	x			x	x	x			x	x
Sarcophagidae		x	x				x				x				x	
Tachinidae		x	x	x			x	x		x	x	x			x	x
Siphonaptera							x									
Hymenoptera		x	x	x			x	x		x	x	x		x	x	x
Symphyta											x					
Cimbicidae			x													
Tenthredinidae			x													
Apocrita																
Braconidae			x	x			x	x		x	x	x			x	x
Ichneumonidae		x	x	x		x	x	x		x	x	x			x	x
Chalcidoidea		x	x	x		x	x	x		x	x	x			x	x
Mymaridae								x			x	x			x	x
Eulophidae		x														
Pteromalidae											x	x				
Cynipoidea				x							x		x		x	x
Cynipidae		x		x			x	x				x			x	x
Evaniidae											x					
Proctotrupoidea		x	x	x		x	x	x		x	x	x			x	x
Proctotrupidae			x							x	x					
Diapriidae				x			x	x			x	x			x	
Platygasteridae				x							x	x				x
Bethyloidea				x												
Dryinidae											x					
Formicidae	x	x	x	x		x	x	x		x	x	x		x	x	x
Vespoidea																
Vespidae							x	x				x				
Pompilidae											x					
Sphecidae				x			x	x			x	x			x	x
Apoidea		x	x				x	x							x	
Halictidae												x			x	x
Apidae		x						x			x	x			x	
Chilopoda		x	x	x												

Table continued on next page.

Taxa	Coastal				Cascade				Central				Eastern			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Diplopoda	x	x		x												x
Chordata																
Amphibia						x										
Salientia	x		x			x										
Ascaphidae																
Ascaphus																
A. truei		x			x	x	x	x								
Agnatha																
Petromyzontiformes																
Petromyzontidae																
Lampetra			x	x												
L. tridentata			x													
L. richardsoni			x													
Osteichthyes			x				x								x	
Salmoniformes																
Salmonidae		x	x					x			x					
Salmo																
S. gairdneri											x	x				
Cypriniformes																
Catostomidae															x	x
Catostomus																
C. macrocheilus															x	x
Cyprinidae																
Rhinichthys																
R. osculus																x
Cottidae		x	x	x											x	
Cottus																
C. confusus		x											x		x	x
C. perplexus				x												x
C. gulosus	x	x	x	x												
Mammalia																
Rodentia																
Zapodidae																
Zapus																
Z. princeps															x	

Appendix 2

Percentage of Samples From Coastal Streams Containing Listed Taxa, by Season and Sample Type

Organisms were tabulated at the family level where possible. Percentages at broader taxonomic levels do not include the indivuduals identified to the family level.

	Benthic				Drift				Sticky				Water			
Taxa	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Number of samples	24	31	43	47	11	15	30	19	16	15	24	23	2	9	14	17
							Percent									
Platyhelminthes																
Turbellaria																
Tricladida																
Planariidae	4.2															
Nematoda	4.2		7.0	2.1											21.4	
Annelida																
Oligochaeta	25.0	29.0	18.6	51.1	18.2	13.3	3.2	5.0					42.9	44.4		
Hirudinea	4.2		2.3	4.3												
Mollusca																
Gastropoda		3.2	4.7		18.2	6.7	19.4	20.0								
Basommatophora																
Lymnaeidae								10.0								
Planorbidae								5.0								
Stylommatophora	4.2															5.9
Mesogastropoda																
Pleuroceridae	25.0	64.5	88.4	76.6	27.3	40.0	83.9	65.0							7.1	
Hydrobiidae	8.3	54.8	58.1	68.1	18.2	40.0	54.8	55.0								
Pelecypoda																
Sphaeriidae			2.3	10.6												
Arthropoda																
Crustacea																
Decapoda																
Astacidae		3.2	20.9	14.9			3.2	5.0								
Isopoda						6.7							14.3	44.4		11.8
Copepoda				2.1												
Arachnida																
Araneae			2.3	2.1		13.3	9.7	25.0	12.5	40.0	12.5	39.1	42.9	88.9	100.0	70.6
Acarina		3.2	16.3	14.9		26.7	25.8	25.0		6.7		4.3	14.3	66.7	50.0	29.4
Opiliones											8.3			22.2	7.1	5.9
Insecta												13.0				
Thysanura																
Machilidae														11.1		
Collembola		3.2		8.5			3.2		43.8	46.7	12.5	17.4	57.1	88.9	57.1	70.6
Sminthuridae					9.1	6.7	3.2	5.0		6.7		17.4		11.1	7.1	5.9
Poduridae																5.9
Isotomidae			4.7		9.1		9.7	15.0		46.7		13.0		11.1	7.1	11.8
Ephemeroptera		6.5	9.3	6.4		53.3	16.1	10.0	31.3	60.0	45.8	43.5	14.3			11.8
Siphlonuridae	25.0	48.4	14.0	2.1	45.5	66.7	16.1	50.0					14.3		7.1	
Baetidae	54.2	90.3	76.7	48.9	72.7	100.0	67.7	90.0		20.0			14.3	44.4	42.9	23.5
Heptageniidae	83.3	100.0	86.0	80.9	45.5	73.3	41.9	40.0	6.3	33.3			14.3	55.6	35.7	23.5
Leptophlebiidae	33.3	71.0	46.5	63.8		46.7	35.5	50.0				4.3				11.8
Ephemerellidae	58.3	93.5	90.7	87.2	36.4	73.3	41.9	45.0			4.2			11.1	7.1	5.9
Odonata																
Anisoptera			2.3													
Gomphidae			2.3													
Coenagrionidae															7.1	
Orthoptera										6.7						5.9
Gryllidae																
Gryllacrididae										20.0	4.2	4.3		44.4		
Dermaptera											4.2					

Table continued on next page

Taxa	Benthic				Drift				Sticky				Water			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
							Percent									
Plecoptera		9.7	11.6	4.3		13.3	22.6	35.0	25.0	33.3	12.5	26.1				5.9
Pteronarcidae						6.7	19.4									11.8
Peltoperlidae			2.3	2.1				5.0								
Taeniopterygidae	37.5		4.7	6.4	9.1	6.7										
Nemouridae	29.2	25.8	32.6	21.3	27.3	66.7	38.7	50.0	31.3	53.3	12.5	30.4	57.1	33.3	21.4	
Leuctridae	12.5	6.5	16.3	4.3		20.0	6.5	30.0						44.4		
Capniidae	37.5	19.4	11.6	29.8	18.2		6.5	75.0				4.3	14.3	11.1		
Perlidae	16.7	54.8	83.7	72.3		6.7	25.8	5.0							7.1	
Perlodidae	50.0	64.5	41.9	40.4	9.1	33.3	29.0	25.0							7.1	
Chloroperlidae	54.2	100.0	97.7	93.6	18.2	33.3	38.7	50.0		13.3	16.7			22.2	35.7	
Psocoptera			2.3				6.5	5.0							28.6	41.2
Mallophaga															7.1	
Thysanoptera														33.3	14.3	5.9
Hemiptera			2.3			6.7	12.9	20.0		6.7	4.2	13.0		11.1	42.9	
Macroveliidae																5.9
Gerridae				2.1		6.7	6.5	10.0		20.0	16.7	13.0	28.6	77.8	42.9	52.9
Veliidae							3.2	5.0		20.0	4.2	21.7		33.3	7.1	11.8
Mesoveliidae										13.3						
Saldidae										13.3	41.7				57.1	
Miridae				2.1										11.1	14.3	
Tingidae						13.3				13.3				11.1	7.1	5.9
Aradidae							3.2									
Lygaeidae						13.3	3.2			13.3	4.2	4.3			14.3	
Pentatomidae							3.2									5.9
Homoptera							9.7	10.0		6.7	8.3	8.7	14.3		35.7	23.5
Cicadellidae			4.7	4.3	9.1			15.0	6.3	20.0	37.5	26.1	14.3		78.6	29.4
Cercopidae			2.3					10.0				13.0			7.1	52.9
Psyllidae										13.3		4.3			28.6	11.8
Aphididae			2.3			6.7	9.7	45.0		33.3	12.5	34.8	14.3	22.2	78.6	64.7
Eriosomatidae							3.2									
Coccoidea						6.7										5.9
Chermidae																5.9
Coleoptera	4.2	3.2	4.7	2.1	9.1	13.3	6.5	5.0	12.5	53.3	37.5	13.0		11.1	57.1	5.9
Lathridiidae										6.7						11.8
Carabidae														11.1	7.1	5.9
Amphizoidae							3.2	10.0								
Dytiscidae			30.2	12.8	9.1	33.3	16.1			6.7	4.2	4.3				
Melyridae															7.1	
Gyrinidae													14.3			
Histeridae															7.1	
Hydrophilidae			4.7			13.3	6.5	20.0		13.3	16.7	4.3		22.2	42.9	5.9
Hydraenidae														22.2	7.1	
(Limnebiidae)										13.3	4.2	4.3		11.1	28.6	11.8
Ptiliidae										33.3	20.8		28.6	33.3	57.1	
Chrysomelidae				2.1			22.6									
Staphylinidae						26.7	9.7	10.0	31.3	60.0	54.2	13.0	28.6	88.9	85.7	29.4
Colydiidae							3.2	5.0								
Cantharidae						6.7				13.3	4.2			44.4		
Curculionidae																
(Nemonychidae)										6.7		4.3			7.1	
Elateridae							3.2					4.3			7.1	
Byrrhidae									6.3			8.7				11.5
Dascillidae															14.3	
Elmidae	50.0	96.8	100.0	100.0	27.3	53.3	67.7	75.0			16.7			11.1	35.7	17.6
Scolytidae										6.7				11.1	28.6	
Cryptophagidae														11.1		
Nitidulidae		6.5												11.1	7.1	
Endomychidae	4.2															

Table continued on next page

Taxa	Benthic				Drift				Sticky				Water			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
								Percent								
Coccinellidae															14.3	11.8
Cerambycidae														11.1		
Anthicidae															7.1	
Neuroptera										6.7						
Sialidae			4.7	10.6			3.2									
Corydalidae							3.2									
Hemerobiidae															14.3	
Trichoptera	4.2	12.9	4.7	6.4		26.7	16.1	10.0	43.8	93.3	75.0	82.6		22.2	7.1	
Limnephilidae	66.7	87.1	83.7	57.4	81.8	73.3	35.5	75.0	6.3	20.0		8.7	14.3	55.6	21.4	29.4
Philopotamidae			32.6			13.3	29.0					8.7	28.6	11.1	35.7	35.3
Rhyacophilidae	58.3	71.0	72.1	68.1	9.1	40.0	22.6	35.0		26.7				77.8	28.6	29.4
Hydropsychidae	12.5	58.1	11.6	40.4		20.0	6.5	35.0						22.2	14.3	
Psychomyiidae		29.0		29.8		6.7	3.2								28.6	
Polycentropodidae			2.3												7.1	
Brachycentridae	20.8	3.2			9.1	53.3	6.5	30.0		6.7						
Calamoceratidae								5.0								
Lepidostomatidae	4.2	6.5	4.7	36.2	18.2	33.3	22.6	70.0		6.7		4.3		55.6	14.3	11.8
Glossosomatidae	33.3	41.9	44.2	44.7	18.2	6.7	6.5	25.0						22.2	7.1	17.6
Phryganeidae															7.1	
Hydroptilidae				2.1									14.3		42.9	
Lepidoptera				4.3		6.7	6.5	5.0			12.5	30.4		11.1	21.4	11.8
Lycaenidae				2.1												
Satyridae												4.3				
Hesperiidae				2.1												
Geometridae														11.1	50.0	5.9
Microlepidoptera										13.3	4.2				7.1	
Pyralidae																5.9
Diptera		3.2	4.7	2.1	9.1		19.4	10.0	12.5	66.7	20.8	30.4			14.3	52.9
Nematocera									31.3	13.3		34.8				
Tanyderidae														22.2		5.9
Tipulidae	79.2	90.3	97.7	95.7	18.2	40.0	16.1	5.0	31.3	100.0	62.5	60.9	57.1	77.8	100.0	70.6
Psychodidae	29.2	3.2	14.0	76.6	36.4	20.0	6.5	35.0	6.3	33.3	4.2		42.9	77.8	50.0	35.3
Ptychopteridae	8.3	3.2		10.6												
Dixidae			4.7		9.1	6.7	22.6	65.0	31.3	40.0	4.2	8.7	28.6	44.4	57.1	64.7
Culicidae										13.3		4.3				5.9
Ceratopogonidae	8.3	12.9	7.0	29.8	9.1					26.7	8.3	34.8			100.0	11.8
Chironomidae	75.0	90.3	86.0	83.0	63.6	73.3	90.3	95.0	87.5	100.0	83.3	87.0	100.0	100.0	100.0	88.2
Simulidae	41.7	16.1	9.3	10.6	36.4	80.0	48.4	40.0	12.5	6.7	20.8	4.3	14.3	44.4	42.9	17.6
Bibionidae						6.7				13.3				11.1		
Mycetophilidae									56.3	73.3	45.8	52.2	28.6	88.9	64.3	58.8
Sciaridae			4.7			33.3	25.8	15.0	31.3	73.3	66.7	56.5	28.6	88.9	92.9	76.5
Cecidiomyiidae						6.7				26.7	16.7	21.7		44.4	100.0	47.1
Brachycera																
Stratiomyidae																5.9
Tabanidae	4.2		2.3												7.1	
Rhagionidae											25.0			11.1		35.7
Therevidae															7.1	
Asilidae										6.7	50.0				21.4	
Empididae	12.5	25.8	20.9	25.5		6.7	32.3	5.0	56.3	86.7	100.0	82.6	14.3	88.9	100.0	64.7
Dolichopodidae							6.5	5.0	56.3	93.3	95.8	100.0	57.1	55.6	100.0	52.9
Acroceridae															7.1	
Cyclorrhapha																
Lonchopteridae												4.3			28.6	
Phoridae						6.5	5.0	18.8	33.3	25.0	17.4	28.6	77.8	57.1	41.2	

Table continued on next page.

Taxa	Benthic				Drift				Sticky				Water			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
							Percent									
Pipunculidae							3.2									5.9
Syrphidae										40.0	12.5				7.1	11.8
Lauxaniidae															7.1	
Lonchaeidae										6.7						
Sphaeroceridae										13.3	12.5		14.3	22.2	64.3	11.8
Milichiidae															7.1	
Tephritidae														11.1		
Ephydridae						26.7			6.3	20.0	20.8	39.1	14.3	55.6	100.0	35.3
Drosophilidae										46.7		13.0		22.2	28.6	
Chloropidae		3.2								6.7		4.3			7.1	
Agromyzidae										13.3		4.3		11.1	7.1	
Clusiidae													14.3	11.1	14.3	
Sciomyzidae																5.9
Heleomyzidae							3.2									
Anthomyzidae															7.1	
Anthomyiidae (Scatophagidae)		3.2					3.2			33.3				44.4	14.3	29.4
Platypezidae									31.3	13.3		34.8				
Muscoidea									37.5	33.3	87.5	56.5				5.9
Muscidae										6.7				44.4	50.0	17.6
Oestroidea																
Calliphoridae															21.4	
Sarcophagidae														11.1	21.4	
Tachinidae										13.3		4.3			21.4	
Hymenoptera						6.7	3.2			26.7	4.2	17.4		11.1	21.4	5.9
Symphyta																
Cimbicidae							3.2									
Tenthredinidae							3.2								7.1	
Apocrita																
Braconidae							3.2	5.0								
Ichneumonidae							3.2			26.7	20.8	17.4		44.4	28.6	17.6
Chalcidoidea						6.7		5.0		13.3	4.2	8.7		44.4	50.0	47.1
Eulophidae														11.1		
Cynipoidea																5.9
Cynipidae						6.7						8.7				
Proctotrupoidea				2.1			3.2	5.0			12.5	4.3		22.2	21.4	17.6
Proctotrupidae															7.1	
Diapriidae												4.3				
Platygasteridae												4.3				
Bethyloidea												4.3				
Formicidae					9.1	6.7	6.5	15.0	6.3	13.3	4.2			11.1	35.7	11.8
Vespoidea																
Sphecidae				2.1												5.9
Apoidea							3.2							11.1	7.1	
Apidae														11.1		
Chilopoda								10.0						33.3	7.1	11.8
Diplopoda					9.1							4.3		11.1		29.4
Chordata																
Amphibia																
Salientia	4.2		2.3													
Ascaphidae		3.2														
Agnatha																
Petromyzontiformes																
Petromyzontidae				2.1			29.0									
Osteichthyes							3.2									
Salmoniformes																
Salmonidae						6.7	3.2									
Cypriniformes																
Cottidae	12.5	19.4	27.9	25.5	9.1		35.5	20.0								

Table continued on next page

Percentage of Samples From Cascade Streams Containing Listed Taxa, by Season and Sample Type

Taxa	Benthic				Drift				Sticky				Water			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
							Percent									
Platyhelminthes																
Turbellaria																
Tricladida																
Planariidae	25.0	51.7	45.7	39.6		13.3	17.9	4.8							6.3	
Nematomorpha							3.6									
Nematoda	6.3	3.4	2.9	31.3			3.6								12.5	
Annelida																
Oligochaeta	50.0	75.9	37.1	54.2	58.3	33.3	17.9	4.8						6.7		
Mollusca																
Gastropoda		6.9			8.3											
Arthropoda																
Crustacea																
Amphipoda								4.8								
Ostracoda	6.3			10.4												
Arachnida																
Araneae				4.2	8.3	6.7	17.9				50.0	9.1		20.0	100.0	72.7
Acarina			17.1		8.3	33.3	25.0	14.3							50.0	18.2
Opiliones											8.3	4.5			6.3	
Insecta							3.6	4.8								
Thysanura																
Machilidae																9.1
Collembola	6.3			12.5	8.3	20.0		23.8	87.5	87.5	8.3	72.7		53.3	87.5	63.6
Sminthuridae														13.3		9.1
Poduridae							3.6									
Isotomidae	12.5				33.3	26.7	7.1	28.6						33.3	6.3	36.4
Ephemeroptera	18.8	24.1	25.7	4.2	25.0	40.0	67.9	38.1		12.5	100.0	40.9		6.7	18.8	9.1
Siphlonuridae	37.5	48.3	68.6	87.5	75.0	86.7	60.7	42.9			4.2				31.3	36.4
Baetidae	87.5	96.6	97.1	79.2	100.0	100.0	96.4	85.7		6.3				20.0	81.3	36.4
Heptageniidae	100.0	100.0	100.0	87.5	100.0	100.0	78.6	71.4		6.3	8.3			33.3	75.0	18.2
Leptophlebiidae	56.3	82.8	71.4	87.5	66.7	80.0	57.1	33.3							6.3	
Ephemerellidae	100.0	96.6	97.1	87.5	100.0	100.0	85.7	61.9			8.3			6.7	56.3	
Odonata																
Anisoptera											4.2					
Orthoptera																
Gryllacrididae											37.5	4.5		6.7	25.0	18.2
Acrididae															6.3	9.1
Plecoptera	37.5	44.8	28.6	31.3	50.0	20.0	21.4	28.6		6.3	16.7	13.6			6.3	9.1
Pteronarcidae		6.9	11.4	2.1				4.8								
Peltoperlidae	75.0	82.8	77.1	64.6	75.0	80.0	39.3	57.1			4.2				25.0	9.1
Taeniopterygidae	62.5	72.4	5.7	6.3	100.0	80.0		19.0								
Nemouridae	43.8	79.3	51.4	85.4	100.0	86.7	50.0	85.7	25.0	75.0	50.0	13.6		33.3	81.3	45.5
Leuctridae	25.0	37.9	34.3	27.1	83.3	86.7	10.7	14.3						46.7		9.1
Capniidae	87.5	34.5	14.3	25.0	91.7	46.7	10.7	38.1						33.3		9.1
Perlidae	81.3	79.3	88.6	91.7	25.0	13.3	32.1	14.3						6.7	18.8	9.1
Perlodidae	37.5	48.3	80.0	58.3	33.3	26.7	42.9	47.6						6.7	6.3	
Chloroperlidae	81.3	96.6	82.9	95.8	83.3	73.3	28.6	42.9			54.2			6.7	87.5	9.1
Psocoptera				2.1			3.6	23.8							81.3	54.5
Mallophaga															31.3	9.1
Thysanoptera			2.9								4.2				81.3	
Hemiptera					8.3		7.1								31.3	9.1
Gerridae			2.9				3.6	4.8			16.7			6.7	12.5	9.1
Coreidae							3.6									
Saldidae								4.8			58.3				68.8	9.1
Miridae															18.8	9.1
Nabidae															6.3	
Tingidae							3.6								6.3	

Table continued on next page

Taxa	Benthic				Drift				Sticky				Water			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
	Percent															
Lygaeidae	7.1								12.5							
Homoptera			2.9				7.1	4.8							18.8	9.1
Cicadellidae			2.9				7.1	14.3			50.0	36.4		6.7	75.0	27.3
Cercopidae							10.7				8.3	4.5			6.3	
Delphacidae														6.7	12.5	
Achilidae															6.3	
Psyllidae								4.8						6.7	25.0	9.1
Aphididae				2.1			39.3	38.1				4.5			100.0	54.5
Coleoptera			2.9		16.7		25.0	4.8			37.5	18.2			43.8	
Lathridiidae															12.5	
Noteridae			5.7					4.8								
Carabidae			2.9				10.7				8.3				68.8	
Amphizoidae					16.7		10.7	14.3								9.1
Dytiscidae			2.9	2.1		6.7	14.3	14.3			4.2					
Melyridae						6.7										
Histeridae															25.0	
Hydrophilidae	6.3		5.7		25.0	20.0	53.6	23.8			33.3				56.3	9.1
Hydraenidae (Limnebiidae)					16.7	20.0	7.1	28.6								
Melandryidae															6.3	
Scarabaeidae															6.3	
Cicindelidae							3.6									
Ptiliidae															31.3	
Chrysomelidae							14.3				4.2				18.8	9.1
Staphylinidae			2.9		8.3	33.3	25.0	33.3			16.7	72.7			93.8	72.7
Pselaphidae							3.6									
Meloidae															12.5	
Cantharidae							7.1				4.2				6.3	
Lampyridae							7.1									
Curculionidae (Nemonychidae)							10.7	9.5				4.5			12.5	9.1
Cleridae							3.6								37.5	
Elateridae					8.3		3.6				8.3				18.8	
Eucnemidae			2.9													
Buprestidae											8.3				31.3	
Dascillidae															6.3	
Ptilodactylidae						6.7										
Helodidae														6.7		
Limnichidae															6.3	
Psephenidae							7.1								6.3	
Elmidae	25.0	58.6	77.1	85.4	58.3	60.0	60.7	52.4		6.3	12.5			6.7	25.0	18.2
Scolytidae							3.6				4.2				6.3	
Derodontidae							3.6	4.8								
Cryptophagidae															12.5	
Bostrichidae							3.6									
Nitidulidae							3.6	4.8							25.0	
Cucujidae											4.2					
Endomychidae							3.6									
Coccinellidae											8.3				12.5	
Cerambycidae							7.1				4.2				18.8	
Anthicidae															37.5	
Mordellidae											8.3				50.0	
Tenebrionidae							3.6									
Neuroptera		3.4		2.1												
Sialidae	6.3			2.1	16.7			4.8			4.2				18.8	
Corydalidae	25.0	20.7	42.9	31.3			3.6									

Table continued on next page.

Taxa	Benthic				Drift				Sticky				Water			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
							Percent									
Hemerobiidae						6.7										
Chrysopidae						6.7					4.2					
Trichoptera	6.3	10.3	22.9	25.0	33.3	20.0	35.7	19.0	12.5	25.0	100.0	54.5		6.7	18.8	9.1
Limnephilidae	25.0	44.8	22.9	66.7	91.7	73.3	25.0	52.4		6.3	12.5	4.5			62.5	54.5
Philopotamidae	6.3		17.1	6.3	16.7	26.7	14.3	9.5							87.5	9.1
Rhyacophilidae	100.0	69.0	80.0	79.2	91.7	86.7	75.0	38.1							93.8	63.6
Hydropsychidae	43.8	44.8	51.4	31.3	66.7	40.0	32.1	33.3							87.5	
Psychomyiidae	6.3					13.3	7.1									
Polycentropodidae	6.3	10.3	2.9	4.2	8.3	6.7		9.5							6.3	
Brachycentridae	6.3	3.4	2.9	18.8	66.7	66.7	25.0	38.1								
Calamoceratidae				2.1		6.7										
Lepidostomatidae	25.0	27.6	40.0	29.2	75.0	60.0	32.1	4.8							56.3	9.1
Glossosomatidae	93.8	75.9	2.9	33.3	58.3	46.7	25.0	23.8							68.8	
Phryganeidae			2.9													
Hydroptilidae				8.3			3.6	4.8							31.3	
Lepidoptera						6.7	10.7	4.8			16.7	18.2			25.0	
Plerdae															6.3	
Lycaenidae															12.5	
Hesperiidae															6.3	
Geometridae							3.6								18.8	9.1
Microlepidoptera							14.3				8.3				43.8	
Pyralidae							7.1									
Aegeriidae																
(Sesiidae)											12.5				12.5	
Diptera		3.4	8.6			13.3	17.9	9.5	12.5	12.5	4.2	9.1		13.3	25.0	27.3
Nematocera									50.0			45.5				
Tanyderidae															12.5	18.2
Tipulidae	68.8	89.7	82.9	91.7	91.7	66.7	64.3	42.9	12.5	25.0	83.3	54.5		80.0	93.8	36.4
Psychodidae	12.5			2.1	25.0	13.3	7.1	14.3		6.3	12.5	4.5		20.0	81.3	36.4
Blephariceridae	6.3	3.4			66.7	60.0	7.1				45.8			6.7	43.8	
Deuterophlebiidae						13.3										
Dixidae			5.7		8.3	20.0	25.0	28.6	12.5					6.7	62.5	63.6
Culicidae															6.3	
Ceratopogonidae		17.2	20.0	25.0	25.0		25.0	14.3			4.2	9.1			100.0	
Chironomidae	68.8	86.2	100.0	97.9	91.7	100.0	89.3	90.5	50.0	68.8	100.0	68.2		100.0	100.0	90.9
Simuliidae	18.8	37.9	20.0	2.1	100.0	93.3	57.1	19.0	12.5	12.5	12.5			13.3	31.3	
Bibionidae						6.7										
Mycetophilidae					8.3	46.7	25.0	28.6	37.5	43.8	83.3	95.5		60.0	87.5	90.9
Sciaridae			5.7			26.7	57.1	28.6		18.8	79.2	54.5		13.3	100.0	63.6
Cecidiomyiidae											4.2	4.5			100.0	54.5
Brachycera																
Stratiomyidae								4.8								
Tabanidae			2.9												6.3	
Rhagionidae							3.6								12.5	
Periscelididae															6.3	
Asilidae											50.0				50.0	
Acroceridae															31.3	
Bombyliidae															12.5	
Empididae	6.3	34.5	54.3	31.3	25.0	33.3	75.0	19.0	75.0	87.5	95.8	100.0		86.7	100.0	81.8
Dolichopodidae			2.9			13.3	7.1		12.5	6.3	100.0	36.4		6.7	75.0	27.3
Cyclorrhapha																
Lonchopteridae															43.8	
Phoridae					8.3	6.7	21.4	14.3			8.3	4.5		33.3	87.5	54.5
Platypezidae									50.0			45.5				
Pipunculidae											4.2					

Table continued on next page.

Taxa	Benthic				Drift				Sticky				Water			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
							Percent									
Syrphidae			2.9					4.8			33.3				25.0	
Conopidae															6.3	
Sepsidae															25.0	
Lauxaniidae															31.3	
Lonchaeidae														6.7		
Sphaeroceridae							3.6									
Milichiidae															56.3	
Tephritidae															6.3	9.1
Ephydridae					8.3	13.3	14.3	4.8		6.3	33.3	4.5				27.3
Drosophilidae						6.7	3.6								18.8	9.1
Chloropidae						6.7									6.3	
Agromyzidae															12.5	
Sciomyzidae							3.6									
Heleomyzidae														6.7		
Anthomyzidae							3.6								68.8	
Anthomyiidae (Scatophagidae)													25.0			
Muscoidea						6.7	3.6		12.5	25.0	95.8	86.4				
Muscidae												4.5		13.3	56.3	18.2
Oestroidea																
Calliphoridae												6.7	6.3			
Sarcophagidae															25.0	
Tachinidae							3.6								56.3	27.3
Siphonaptera																
Hymenoptera							7.1	4.8			16.7	22.7				
Apocrita																
Braconidae							17.9	4.8								
Ichneumonidae							14.3	4.8			8.3	13.6		6.7	43.8	
Chalcidoidea						6.7	25.0	9.5			4.2	4.5				
Myrmaridae																
Cynipoidea																
Cynipidae							10.7	4.8								
Prototrupoidea							14.3	9.5			4.2			13.3		27.3
Diapriidae							3.6	4.8								
Formicoidea																
Formicidae						6.7	28.6	19.0			33.3	18.2				9.1
Vespoidea																
Vespidae															6.3	9.1
Sphecidae															25.0	27.3
Apoidea											4.2					9.1
Apidae																9.1
Chordata																
Amphibia						6.7										
Salientia		3.4														
Ascaphidae		3.4	2.9		16.7	20.0		4.8						6.7	18.8	
Osteichthyes							3.6									
Salmoniformes																
Salmonidae				2.1												

Table continued on next page

Percentage of Samples From Central Streams Containing Listed Taxa, by Season and Sample Type

Taxa	Benthic				Drift				Sticky				Water			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
							Percent									
Platyhelminthes																
Turbellaria																
Tricladida																
Planariidae	31.3	26.7	35.4	44.4	12.5	26.7	4.3	12.0								
Nematoda		6.7	10.4	11.1											9.1	
Annelida																
Oligochaeta	56.3	60.0	50.0	75.6	12.5	26.7	4.3	20.0						9.1		
Mollusca																
Gastropoda															9.1	
Basommatophora																
Physidae				6.7												
Planorbidae				2.2			4.3									
Mesogastropoda																
Hydrobiidae			4.2	2.2		6.7	4.3									
Pelecypoda						6.7										
Sphaeriidae	6.3			4.4												
Arthropoda																
Crustacea																
Amphipoda		3.3	4.2	2.2												
Ostracoda				2.2												
Copepoda				2.2												
Arachnida																
Araneae			2.1	4.4		13.3	39.1	36.0		28.6	72.7	41.7		36.4	72.7	73.3
Acarina	6.3		14.6	6.7			13.0	28.0		7.1		12.5		9.1	54.5	6.7
Pseudoscorpionida											4.5				9.1	
Opiliones												4.2				
Insecta						6.7				14.3	4.5					
Thysanura																
Machilidae							8.7									
Collembola				2.2			4.3	24.0		57.1	4.5	12.5			9.1	6.7
Sminthuridae						6.7				21.4		8.3		36.4		
Isotomidae						13.3	8.7	8.0		42.9	18.2	20.8		81.8	54.5	86.7
Ephemeroptera			10.4	8.9			39.1	20.0		21.4	86.4	41.7			27.3	40.0
Siphlonuridae	18.8	3.3	52.1	24.4	62.5	60.0	47.8	40.0		7.1						26.7
Baetidae	75.0	86.7	93.8	77.8	75.0	100.0	78.3	88.0		7.1		4.2			9.1	60.0
Heptageniidae	87.5	80.0	83.3	91.1	75.0	93.3	56.5	88.0		14.3				27.3	27.3	13.3
Leptophlebiidae	56.3	36.7	20.8	46.7	50.0	13.3	43.5	52.0							9.1	6.7
Ephemerellidae	87.5	83.3	91.7	91.1	75.0	86.7	82.6	84.0		7.1	13.6			9.1	27.3	13.3
Odonata																
Gomphidae			2.1													
Cordulegastridae	6.3			4.4												
Libellulidae						6.7										
Orthoptera			2.1				8.7				18.2					
Tetrigidae								4.0						9.1		6.7
Gryllidae							4.3									
Dermaptera																
Forficulidae												4.2				6.7
Plecoptera			16.7	2.2			8.7	8.0		42.9	18.2	12.5				6.7
Pteronarcidae	6.3	3.3	2.1	6.7				8.0								
Taeniopterygidae				2.2											9.1	
Nemouridae	100.0	76.7	31.3	66.7	87.5	93.3	21.7	92.0		71.4	31.8	12.5		90.9	36.4	40.0
Leuctridae	6.3	10.0		11.1				8.0		7.1				27.3		
Capniidae	50.0	16.7		53.3	62.5	20.0	8.7	72.0		7.1				36.4		13.3
Perlidae	75.0	73.3	81.3	82.2			13.0	24.0								
Perlodidae	31.3	6.7	41.7	71.1		13.3	30.4	20.0						27.3	18.2	
Chloroperlidae	81.3	76.7	89.6	91.1	62.5		21.7	60.0			22.7				9.1	
Psocoptera			2.1	2.2			8.7	12.0							9.1	6.7
Thysanoptera						6.7		4.0			4.5				63.6	26.7
Hemiptera			10.4				13.0	12.0		7.1	18.2	4.2			27.3	26.7
Corixidae					12.5		13.0	8.0								
Neididae							4.3									
Gerridae			2.1				26.1	12.0		7.1	13.6	4.2		9.1	9.1	6.7
Veliidae							4.3	8.0								
Saldidae							4.3				63.6				54.5	6.7
Anthocoridae							8.7									
Miridae							8.7	4.0							27.3	
Nabidae							8.7								9.1	
Reduviidae								4.0			4.5					
Tingidae							8.7									
Aradidae							4.3									
Lygaeidae							8.7								27.3	

Table continued on next page

Taxa	Benthic				Drift				Sticky				Water			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
							Percent									
Homoptera			2.1	2.2			8.7	8.0		14.3	27.3	12.5		36.4	36.4	6.7
Cicadellidae		3.3	27.1	13.3			52.2	80.0		28.6	81.8	91.7		45.5	63.6	73.3
Cercopidae			6.3				4.3	4.0				4.2		9.1		
Delphacidae															9.1	
Psyllidae		3.3		2.2			26.1	28.0		7.1	9.1	29.2			45.5	53.3
Aphididae			10.4	2.2		6.7	52.2	68.0		28.6	31.8	45.8			72.7	93.3
Eriosomatidae							4.3									33.3
Coccoidea								8.0						9.1		
Coleoptera							30.4	12.0		7.1	36.4	16.7		18.2	27.3	13.3
Cupedidae															18.2	
Silphidae							4.3									
Lathridiidae							4.3									
Carabidae							4.3	12.0			4.5	4.2		9.1		
Haliplidae				2.2			4.3									
Amphizoidae							4.3	16.0								
Dytiscidae	12.5	6.7	6.3	20.0		6.7	52.2	32.0			9.1					
Gyrinidae								4.0								
Hydrophilidae	6.3				12.5	6.7	60.9	40.0			4.5	4.2		18.2	18.2	6.7
Hydraenidae (Limnebiidae)		6.7	2.1		12.5		21.7	28.0						36.4	9.1	
Melandryidae							4.3								9.1	
Scarabaeidae							13.0				4.5				9.1	
Ptiliidae											4.5				27.3	20.0
Chrysomelidae		3.3	2.1				43.5	12.0		21.4	22.7	20.8		54.5	18.2	33.3
Scaphidiidae							8.7									13.3
Staphylinidae						13.3	39.1	44.0		14.3	27.3	58.3		72.7	45.5	46.7
Colydiidae															9.1	
Scydmaenidae								4.0								
Cantharidae							8.7								18.2	
Curculionidae (Nemonychidae)							8.7				4.5	4.2		9.1	18.2	
Malachiidae															9.1	
Cleridae							4.3	8.0						9.1	9.1	
Elateridae															9.1	
Buprestidae										17.4	4.0			9.1		
Helodidae								4.0								
Dryopidae							4.3	12.0								
Elmidae	87.5	70.0	91.7	93.3	37.5	26.7	65.2	84.2			18.2	4.2			27.3	
Scolytidae							4.3	4.0							9.1	6.7
Derodontidae											4.5					6.7
Nitidulidae														9.1	27.3	6.7
Coccinellidae							4.3									
Cerambycidae			2.1				13.0								18.2	
Pedilidae								4.0								
Cephaloidae															9.1	
Mordellidae							4.3				9.1				9.1	
Tenebrionidae							8.7									
Neuroptera												4.2				
Sialidae		3.3														
Raphidiidae							4.3				4.5					
Coniopterygidae							4.3									
Hemerobiidae								4.0								
Trichoptera	25.0	6.7	37.5	24.4	12.5		30.4	28.0		21.4	90.9	66.7			27.3	6.7
Limnephilidae	62.5	76.7	85.4	55.6	62.5	80.0	78.3	76.0			13.6	29.2		18.2	27.3	53.3
Philopotamidae			14.6	2.2			4.3	12.0							27.3	60.0
Rhyacophilidae	56.3	76.7	45.8	71.1	12.5	26.7	13.0	40.0						18.2	72.7	60.0
Hydropsychidae	68.8	66.7	50.0	73.3	37.5	13.3	26.1	52.0							36.4	26.7
Psychomyiidae				2.2			4.3									6.7

Table continued on next page.

Taxa	Benthic				Drift				Sticky				Water			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
							Percent									
Polycentropodidae				4.4		6.7										
Brachycentridae	43.8	43.3	14.6	42.2	25.0	33.3	26.1	44.0							18.2	6.7
Lepidostomatidae	56.3	36.7	16.7	51.1	25.0	53.3	43.5	48.0				4.2		9.1	36.4	6.7
Glossosomatidae	25.0	3.3	47.9	26.7			17.4	4.0							9.1	20.0
Phryganeidae																13.3
Lepidoptera			2.1			6.7	21.7	16.0		7.1	31.8	29.2			27.3	6.7
Satyridae																6.7
Hesperiidae																26.7
Arctiidae															18.2	13.3
Noctuidae														9.1	45.5	13.3
Geometridae															9.1	6.7
Microlepidoptera							17.4	8.0		7.1	18.2	4.2			27.3	
Diptera		3.3	12.5	4.4	12.5		43.5	36.0		50.0	36.4	25.0			27.3	20.0
Nematocera										28.6	45.5	25.0				6.7
Tipulidae	93.8	80.0	77.1	80.0	12.5	40.0	43.5	28.0		21.4	86.4	37.5		36.4	72.7	46.7
Psychodidae	81.3	63.3	4.2	91.1	62.5	20.0	26.1	64.0		7.1	27.3	4.2			63.6	20.0
Blepharoceridae		10.0				6.7					4.5				18.2	6.7
Dixidae							34.8	28.0		14.3	13.6	16.7		9.1	27.3	73.3
Culicidae								4.0								
Ceratopogonidae	25.0	23.3	22.9	51.1			26.1	20.0		7.1	4.5	4.2			63.6	33.3
Chironomidae	100.0	96.7	100.0	95.6	100.0	86.7	95.7	92.0		100.0	100.0	100.0		81.8	90.9	100.0
Simuliidae	18.8	70.0	18.8		37.5	66.7	65.2	16.0		7.1	13.6	4.2		27.3	63.6	13.3
Bibionidae								24.0								20.0
Mycetophilidae				2.2			26.1	44.0		35.7	50.0	75.0		72.7	72.7	100.0
Sciaridae							69.6	56.0		35.7	40.9	83.3		27.3	72.7	9.3
Cecidiomyiidae							34.8	4.0		14.3	4.5	12.5		9.1	72.7	46.7
Brachycera																
Xylomyidae											4.5					
Stratiomyidae	6.3		2.1	2.2							4.5					
Tabanidae	12.5	3.3	16.7	17.8		6.7	8.7				4.5					
Rhagionidae											13.6				27.3	
Therevidae											9.1					6.7
Asilidae											9.1	4.2			9.1	13.3
Acroceridae															27.3	
Empidae	18.8	16.7	18.8	46.7			43.5	24.0		50.0	95.5	87.5		18.2	72.7	86.7
Dolichopodidae			2.1	4.4			8.7	16.0		14.3	100.0	66.7		9.1	63.6	33.3
Cyclorrhapha															9.1	
Lonchopteridae			2.1													6.7
Phoridae							13.0	12.0		7.1	18.2	12.5		45.5	36.4	40.0
Pipunculidae							4.3				4.5					20.0
Syrphidae								8.0			22.7				9.1	6.7
Sepsidae										7.1					9.1	6.7
Lonchaeidae														9.1		
Sphaeroceridae								4.0						18.2		6.7
Ephydridae			4.2				39.1	16.0		21.4	27.3	20.8		36.4	72.7	73.3

Table continued on next page.

Taxa	Benthic				Drift				Sticky				Water			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
							Percent									
Drosophilidae							8.7	12.0							18.2	[illegible]
Chloropidae							13.0	4.0			13.6				18.2	6.7
Agromyzidae							4.3									[illegible]
Heleomyzidae																6.7
Anthomyzidae							4.3									
Anthomyiidae (Scatophagidae)							13.0	24.0		14.3	4.5	8.3		36.4	54.5	73.3
Muscoidea								4.0		28.6	90.9	62.5			9.1	
Muscidae											9.1	4.2			36.4	33.3
Oestroidea											36.4					
Calliphoridae												4.2			18.2	33.3
Sarcophagidae			4.2												9.1	
Tachinidae							4.3					4.2		9.1	[illegible]	[illegible]
Hymenoptera			4.2	2.2			13.0	40.0		7.1	27.3	8.3			18.2	6.7
Symphyta															9.1	
Apocrita																
Braconidae			2.1				43.5	24.0		7.1	4.5				18.2	26.7
Ichneumonidae			2.1				21.7	12.0		7.1	31.8	16.7		18.2	45.5	6.7
Chalcidoidea							34.8	16.0		7.1		8.3			27.3	20.0
Mymaridae				2.2			4.3				4.5				18.2	6.7
Pteromalidae							4.3	4.0								
Cynipoidea							4.3								18.2	
Cynipidae								4.0								
Evaniidae							4.3								[illegible]	
Proctotrupoidea			2.1				13.0	16.0			18.2	12.5		9.1	36.4	[illegible]
Proctotrupidae							4.3							9.1		
Diapriidae								4.0							18.2	[illegible]
Platygasteridae							4.3	12.0								20.0
Bethyloidea																
Dryinidae							4.3									
Formicidae			8.3	2.2			87.0	40.0		21.4	54.5	25.0		18.2	81.8	53.3
Vespoidea																
Vespidae								4.0				8.3				13.3
Pompilidae							4.3									
Sphecidae							4.3									20.0
Apoidea																
Halictidae																
Apidae															9.1	13.3
Chordata																
Osteichthyes																
Salmoniformes																
Salmonidae				2.2			8.7									

Table continued on next page

Percentage of Samples From Eastern Streams Containing Listed Taxa, by Season and Sample Type

Taxa	Benthic				Drift				Sticky				Water			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
							Percent									
Platyhelminthes																
Turbellaria																
Tricladida																
Planariidae	6.3	3.1	6.0	12.8												
Nematoda			2.0	14.9											18.2	
Annelida																
Oligochaeta	75.0	62.5	22.0	70.2		33.3	4.2	14.3								6.3
Mollusca																
Gastropoda																6.3
Basommatophora																
Physidae	12.5	18.8	12.0	40.4	12.5		12.5	19.0								
Planorbidae				4.3												
Ancylidae	18.8	3.1		17.0												
Mesogastropoda																
Pleuroceridae			2.0													
Hydrobiidae	6.3		2.0													
Pelecypoda																
Margaritanidae			2.0													
Sphaeriidae	6.3	18.8		14.9											9.1	6.3
Unionidae			2.0													
Arthropoda																
Crustacea																
Decapoda																
Astacidae	6.3		24.0	34.0		6.7	12.5	4.8								
Amphipoda		3.1		4.3												
Ostracoda				2.1												
Copepoda				4.3				9.5								
Arachnida																
Araneae			2.0	4.3		6.7	66.7	47.6		13.3	81.0	72.7		20.0	100.0	93.8
Acarina	6.3		14.0	17.0		6.7	37.5	33.3		6.7				10.0	63.6	25.0
Opiliones											9.5					
Insecta			2.0													
Collembola		3.1		2.1	12.5	20.0		38.1		20.0	4.8	4.5		30.0	27.3	37.5
Sminthuridae														10.0		
Isotomidae						26.7		4.8		60.0				40.0		37.5
Ephemeroptera			10.0	10.6	12.5	6.7	16.7	33.3			90.5	40.9			36.4	18.8
Siphlonuridae	37.5	21.9	66.0	55.3	50.0	66.7	41.7	47.6							9.1	25.0
Baetidae	31.3	65.6	64.0	48.9	37.5	73.3	62.5	81.0							72.7	18.8
Heptageniidae	68.8	81.3	98.0	66.0	37.5	80.0	37.5	47.6			4.8			20.0	36.4	18.8
Leptophlebiidae	75.0	37.5	74.0	83.0	25.0	40.0	37.5	81.0				4.5			45.5	6.3
Ephemerellidae	68.8	28.1	68.0	80.9	50.0	33.3	66.7	66.7			14.3				18.2	6.3
Odonata																
Anisoptera							4.2									
Gomphidae				8.5												
Aeshnidae				2.1												
Coenagrionidae															9.1	
Orthoptera				2.1											9.1	
Gryllidae															9.1	
Acrididae			2.0												9.1	
Plecoptera	6.3	6.3	4.0	4.3	12.5	6.7	4.2	9.5		40.0	19.0			10.0	9.1	
Pteronarcidae	6.3															
Taeniopterygidae		3.1		2.1												
Nemouridae	62.5	78.1	34.0	40.4	50.0	100.0	20.8	52.4		93.3	52.4			70.0	45.5	6.3
Leuctridae														30.0		
Capniidae	62.5	53.1	4.0	29.8	75.0	46.7	8.3	4.8		13.3				40.0	9.1	
Perlidae	31.3	31.3	46.0	57.4												
Perlodidae	56.3	15.6	52.0	66.0	12.5	6.7	4.2	14.3						10.0	9.1	
Chloroperlidae	68.8	65.6	60.0	74.5	12.5	26.7	4.2	14.3			66.7				45.5	
Psocoptera			2.0												54.5	18.8
Thysanoptera							4.2	9.5							81.8	18.8
Hemiptera	6.3						8.3				4.8					
Corixidae			4.0	27.7	50.0		4.2	42.9							9.1	6.3
Gerridae			10.0				37.5	14.3			28.6			10.0	27.3	25.0
Coreidae								4.8								
Saldidae											61.9				90.9	18.8
Anthocoridae															9.1	
Miridae															9.1	
Nabidae								4.8								9.1
Reduviidae																6.3
Lygaeidae			2.0												27.3	

Table continued on next page

Taxa	Benthic				Drift				Sticky				Water			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
								Percent								
Homoptera				2.1				14.3		13.3				20.0	18.2	25.0
Cicadellidae			16.0	25.5	12.5	13.3	25.0	61.9		13.3	76.2	68.2		30.0	30.9	68.8
Cercopidae														10.0	27.3	12.5
Delphacidae															36.4	
Psyllidae										13.3				10.0		18.8
Aphididae			2.0			6.7	20.8	71.4			9.5	22.7			100.0	68.8
Eriosomatidae								9.5								12.5
Coleoptera			2.0		12.5	13.3	8.3	19.0		13.3	28.6	27.3			27.3	12.5
Noteridae			2.0													
Carabidae							4.2	9.5			9.5	9.1			45.5	6.3
Haliplidae	6.3		10.0	19.1			4.2	33.3								
Dytiscidae	25.0		22.0	27.7	12.5	20.0	12.5	14.3							18.2	
Histeridae							4.2					4.5				
Hydrophilidae		3.1	2.0		12.5	20.0	16.7	42.9		13.3	19.0	18.2		10.0	54.5	18.8
Hydraenidae (Limnebiidae)	6.3			2.1	50.0	26.7	12.5	47.6		6.7						12.5
Melandryidae															9.1	
Scarabaeidae															18.2	
Ptilidae								4.8							18.2	6.3
Chrysomelidae				2.1			4.2					4.5			27.3	18.8
Staphylinidae					12.5	40.0	16.7	57.1		13.3	14.3	54.5		40.0	72.7	62.5
Scydmaenidae							4.2									
Cantharidae			2.0								4.8				27.3	
Lampyridae															9.1	
Curculionidae (Nemonychidae)								4.8								
Elateridae							4.2				4.8				18.2	
Psephenidae				2.1												
Elmidae	43.8	37.5	98.0	87.2	25.0	6.7	54.2	71.4			4.8				9.1	
Scolytidae						6.7	4.2	4.8			4.8			10.0	18.2	
Bostrichidae							8.3									
Nitidulidae															18.2	
Coccinellidae			2.0				4.2	4.8							9.1	
Cerambycidae															18.2	
Neuroptera											4.8					
Sialidae	12.5	3.1	10.0	55.3	12.5											
Chrysopidae															9.1	
Trichoptera			2.0	8.5		6.7	12.5	14.3		6.7	81.0	45.5				
Limnephilidae	12.5	6.3	20.0	14.9	37.5	40.0	16.7	33.3			4.8				18.2	25.0
Philopotamidae	6.3		12.0													31.3
Rhyacophilidae	12.5	43.8	12.0	8.5		26.7		4.8							54.5	6.3
Hydropsychidae	18.8	12.5	18.0	27.7				42.9							18.2	
Psychomyiidae			4.0	17.0				4.8								
Polycentropodidae															9.1	
Lepidostomatidae	50.0	31.3	10.0	48.9	12.5	6.7		38.1							27.3	
Glossosomatidae	12.5	6.3	12.0	8.5				4.8								
Hydroptilidae	12.5		4.0	17.0			4.2	4.8							54.5	25.0
Leptoceridae															9.1	
Lepidoptera						6.7		4.8			38.1	13.6			27.3	6.3
Satyridae																12.5
Hesperiidae																18.8
Noctuidae															18.2	6.3
Geometridae															54.5	
Microlepidoptera							8.3								72.7	6.3
Pyralidae				17.0		6.7		9.5								
Diptera		3.1	2.0			13.3	4.2	23.8		20.0	4.8	27.3			18.2	12.5
Nematocera								9.5		6.7		4.5			9.1	6.3
Tipulidae	81.3	81.3	74.0	83.0	12.5	33.3	8.3	57.1		6.7	76.2	59.1		10.0	90.9	93.8
Psychodidae	25.0	25.0	4.0	36.2	12.5	6.7	8.3	38.1			9.5				72.7	43.8
Blephariceridae		18.8				6.7		4.8		33.3						
Dixidae						6.7	25.0	71.4							18.2	31.3
Ceratopogonidae		9.4	10.0	23.4		13.3		28.6			4.8	4.5		90.9	43.8	
Chironomidae	93.8	81.3	88.0	91.5	75.0	86.7	70.8	100.0		73.3	85.7	86.4		70.0	100.0	100.0
Simuliidae	31.3	65.6	22.0	4.3		80.0	37.5	28.6		6.7	9.5	4.5		10.0	9.1	25.0
Bibionidae								9.5				4.5				12.5
Mycetophilidae						13.3		19.0		20.0	47.6	68.2		40.0	63.6	87.5

Table continued on next page.

Taxa	Benthic				Drift				Sticky				Water			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
							Percent									
Sciaridae		3.1	4.0	4.3		33.3	20.8	52.4		13.3	52.4	54.5			100.0	81.3
Cecidiomyiidae						6.7		14.3		6.7	19.0	9.1			100.0	43.8
Brachycera																6.3
Stratiomyidae		3.1														
Tabanidae	18.8	9.4	8.0	23.4							14.3				9.1	
Rhagionidae											14.3				27.3	
Pe[illegible]idae															9.1	
Asilidae											61.9				63.6	
Acroceridae															27.3	
Bombyliidae															9.1	
Empidae			10.0	6.4			16.7	19.0		20.0	61.9	100.0		10.0	72.7	62.5
Dolichopodidae			2.0				12.5	14.3			95.2	50.0		30.0	100.0	81.3
Cyclorrhapha															18.2	12.5
Lauxaniidae															9.1	
[illegible]															9.1	6.3
[illegible]idae								33.3			14.3	4.5		10.0	72.7	12.5
Syrphidae											28.6				27.3	
Lonchaeidae														10.0		
Sphaeroceridae										6.7					27.3	
Micropezidae															27.3	6.3
Ephydridae			2.0				20.8	47.6			42.9	22.7		20.0	100.0	81.3
Drosophilidae											4.8				27.3	6.3
Chloropidae															54.5	
Agromyzidae								9.5							36.4	
Clusiidae															9.1	
Sciomyzidae															9.1	
Heleomyzidae															18.2	12.5
Anthomyzidae								4.8		33.3					63.6	75.0
Anthomyiidae (Scatophagidae)															9.1	
Muscoidea								9.5		13.3	95.2	95.5			9.1	6.3
Muscidae														10.0	72.7	31.3
Oestroidea																
Calliphoridae															27.3	25.0
Sarcophagidae															9.1	
Tachinidae															45.5	18.8
Hymenoptera						6.7	12.5	14.3			23.8				36.4	
Apocrita																
Braconidae				2.1			4.2	4.8							9.1	
Ichneumonidae				2.1			16.7	23.8			23.8	4.5			63.6	12.5
Proctotrupoidea							16.7	28.6			4.8	4.5			81.8	12.5
Mymaridae			2.0				4.2	14.3							18.2	12.5
Cynipoidea					12.5			4.8							9.1	6.3
Cynipidae							4.2	4.8								
Proctotrupoidea				2.1				38.1			4.8				45.5	25.0
Diapriidae							4.2									
Platygasteridae								4.8								
Chalcidoidea																
Formicidae						[illegible]	33.3	38.1			42.9			63.6	43.8	
Vespoidea																
Sphecidae															27.3	6.3
Apoidea															9.1	
Halictidae															9.1	6.3
Apidae															9.1	
[illegible]																6.3
Coleoptera																
Curculionidae							8.3									
Lepidoptera																
Catostomidae			2.0	4.3			8.3									
Cyprinidae				2.1												
Cottidae	6.3		18.0	12.8			16.7	4.8							9.1	
Mammalia																
Rodentia																
Soricidae															9.1	

Appendix 3

Summary of Invertebrate Data For Each Season and Sample Type—Coastal Streams

1. Composition

Taxa	Benthic				Drift				Sticky				Water			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
								Percent								
Oligochaeta	0 5	0 2	0 2	0 6	0 6	0 1	0 1						1 5	1 5		
Gastropoda	7	2 3	10.0	5 0	13.0	2 6	15 7	10 1	0 1							
Araneae						1	2	3	5	0 6		1 2	1 5	1 9	3 6	3 4
Acarina			1	1		2	4	2		1		1	5	1 1	5	4
Collembola				1	6	4	2	2	3 7	13 5	0 4	3 0	5 0	13 2	1 0	9 7
Ephemeroptera	65 9	59 3	20 5	17 4	24 5	68 3	41 9	18 5	2 1	1 6	3	1 9	2 0	1 1	1 0	1 4
Orthoptera										6		1		1 0		1
Plecoptera	8 4	11 8	19 8	11 5	6 5	12 4	10 3	27 3	10 3	3 9	2	2 1	6 5	1 2	6	5
Psocoptera							2								2	1 9
Hemiptera						3	6	4		1 3	1	1 0	3 0	3 4	4 1	4 1
Homoptera			1		3	1	3	7	2	1 4	4	2 0	1 5	1	5 7	4 8
Coleoptera	1 9	13 6	27 3	32 3	4 7	3 1	6 8	2 8	3 3	10 0	3 9	9	3 5	3 4	6 1	1 6
Trichoptera	7 0	5 7	10 2	10 3	23 9	5 5	6 0	24 4	2 8	5 4	9	4 4	2 5	4 5	2 6	3 0
Diptera	15 4	7 0	11.1	21.9	24 8	6 7	16.1	14 3	76 8	60 3	92 9	75 6	72 0	64 5	72 6	68 2
Hymenoptera					6	2	3	4	2	1 3	2	1 8		1 4	1 4	2 9
Other [1]	.2	1	.7	8	.5		9	4			1	9	5	1 2	.6	.4

1 Other is the sum of all taxa that did not comprise more than 1 percent of the total number of organisms within that season

2. Number of organisms and sample weights

Parameter	Benthic				Drift				Sticky				Water			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Number of samples	24	31	43	47	11	15	30	19	16	15	24	23	2	9	14	17
Mean number of organisms per sample	76 0	193 1	145 6	163 0	29 3	192 9	95 3	117 8	26 7	130 3	428 5	66 2	28 6	169 8	238 4	81 6
Minimum number of organisms per sample	1	11	42	25	1	8	7	11	6	34	52	16	4	52	161	2
Maximum number of organisms per sample	251	538	479	472	99	1689	391	283	49	406	1694	145	72			
Mean sample weight(g)	050	274	498	210	103	233	501	263					025	206	136	079
Minimum sample weight(g)	002	003	035	021	002	003	.015	.028					000	023	067	001
Maximum sample weight(g)	270	1 064	1 811	812	601	962	1 923	1 223					087	417	264	362

Summary of Invertebrate Data for Each Season and Sample Type—Cascade Streams

1. Composition

Taxa	Benthic				Drift				Sticky				Water			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
								Percent								
Nematoda	0.1	0 2	0 2	1.7											0.1	
Oligochaeta	8	3 3	1 9	2.9	1.1	0.1	0.7	0.1						0.1		
Araneae					.1		.2				0.3	0.1		.5	1.3	1.2
Acarina			.1			1	1.9	.2							2	.1
Collembola	2			5	.3	3	1	6.7	91.2	43 9	9.5	59.7		25 5	23 9	33 0
Ephemeroptera	50 1	60 5	47 2	25 5	34 7	62 5	45 0	22.7		5	1.4	8		1 6	1.2	1.1
Plecoptera	33 5	19 6	17.7	28 4	30 9	10 0	4 3	23.9	6	7 5	1.1	.2		13.4	1.2	1.1
Psocoptera								2 0							.3	1.4
Thysanoptera															1.2	
Hemiptera							2	.1			6			.1	1.8	.3
Homoptera							1.2	1.3			3	.7		5	1.7	2.1
Coleoptera	4	6	3.4	3 4	9	5	4 8	4 5	.1	1.0	1.5			2	3.7	1.7
Neuroptera	3	1	4	4	.1			.1							1.1	
Trichoptera	8 4	3.7	5 7	8 6	18 6	4 1	4 8	5 4	.2	.7	5 5	1.3		1	3.7	1.9
Diptera	4 5	11 4	22.3	26 8	12 9	22 0	35 4	30 9	7.9	46.4	78.9	35.0		57.4	57.1	53 3
Hymenoptera							1.1	1.6			4	.5		4	1 1	2.3
Other[1]	1 7	6	1.1	1.8	.4	.4	3	5			5	1 7		2	.4	5

1/ Other is the sum of all taxa that did not comprise more than 1 percent of the total number of organisms within that season.

2. Number of organisms and sample weights

Parameter	Benthic				Drift				Sticky				Water			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Number of samples	16	29	35	48	12	13	26	21	9	16	24	22		15	16	11
Mean number of organisms per sample	124 3	227 6	144 2	132 2	177 0	576 5	170 4	85 1	77 4	46 4	331.8	129 6		54.7	594 8	131 7
Minimum number of organisms per sample	28	41	30	19	75	75	1	10	4	5	66	13		4	22	45
Maximum number of organisms per sample	238	657	348	396	318	1445	535	251	424	305	2725	617		130	3182	329
Mean sample weight(g)	058	171	141	068	063	240	090	057						166	.673	.093
Minimum sample weight(g)	004	040	021	015	012	041	001	004						001	.091	.001
Maximum sample weight(g)	210	537	587	318	147	575	404	639						1 180	2.788	.279

Summary of Invertebrate Data for Each Season and Sample Type—Central Streams

1. Composition

Taxa	Benthic				Drift				Sticky				Water			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
								Percent								
Tricladida	0.3	0.1	3.3	2 0	0 1	0.1		0 1								
Oligochaeta	1.0	1.7	1.6	1.3	3	2		1								
Araneae						1	0 4	2		0 1	0.4	0 5		0 2	2 9	1 1
Collembola						1	1	2		87 5	44 0	46 8		95 5	9	16 7
Ephemeroptera	31.7	23 0	33.5	34.3	33.6	31 8	39 6	31 7		5	6	1 1		1	4	1 1
Plecoptera	28.1	20.4	11.1	11.9	31.0	37 6	9	12 3		2 7	2	2		8	4	6
Thysanoptera															3 8	2
Hemiptera			.1		1		1.0	2			3				1 3	3
Homoptera			7	.1			8 8	8 5		8	4 4	8 7		2	12 7	5 0
Coleoptera	4.3	2.7	12.9	9.6	4	3	12.5	14 7		2	4	1 7		8	13 2	1 4
Trichoptera	6.9	10 4	16.7	9 3	1 6	3 9	3 2	7 0		2	2 2	11 1		1	5 4	10 6
Diptera	27.6	41.5	19.7	31.1	32.9	25 8	26 3	23 0		7 7	46 9	29 1		2 2	55 7	61 2
Hymenoptera			.1				6 5	1 5		2	6	6		1	2 1	1 6
Other1/	.1	.2	.5	.4		.1	.7	.5		1		2			1 2	4

1/ Other is the sum of all taxa that did not comprise more than 1 percent of the total number of organisms within that season

2. Number of organisms and sample weights

Parameter	Benthic				Drift				Sticky				Water			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Number of samples	16	30	48	45	8	14	21	21		14	22	24	11	11	15	
Mean number of organisms per sample	284.3	330 5	153.0	302.1	235.9	237.5	243.2	340.8		380 7	930 7	221 5		892 5	376 9	222 9
Minimum number of organisms per sample	39	3	23	1	29	10	8	10		21	43	38	5	5	56	
Maximum number of organisms per sample	909	1054	628	765	773	888	1224	1606		2033	11063	2378		5654	1681	459
Mean sample weight(g)	101	200	160	138	.093	.081	096	.085					095	401	162	
Minimum sample weight(g)	.003	001	005	000	.016	.004	.003	.001					038	226	024	
Maximum sample weight(g)	.218	503	1.348	.653	.216	.180	.581	.655					132	732	.451	

Summary of Invertebrate Data for Each Season and Sample Type—Eastern Streams

1. Composition

Taxa	Benthic				Drift				Sticky				Water			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
								Percent								
Oligochaeta	2 3	3 6	0 3	4 0	0 2	0 4	0 4									
Gastropoda	9	2	4	4 4	1.8		3	0.1								
Decapoda	1 0		4	5			3	1								
Araneae							1 6	.4	0 8	1.1	1 8		0 6	2.6	3.3	
Acarina	1		2	1			1 7	1 4	2				6	.4	2	
Collembola					6	4		1 0	53 5				33 6	.1	7.1	
Ephemeroptera	31 1	9 8	41 4	30 6	33 2	5 4	18 8	11.7		7.1	2 5		6	2 0	1 8	
Plecoptera	20 9	31 7	6 9	9 3	41.0	76 0	2 4	1 6	15.3	6 0			40 3	3.2		
Hemiptera	1		2	1.1	2 7		4 3	3		7			9	1 2	.6	
Homoptera			3	8	3	1	2 4	52 8	1.2	8 5	36 7		3.5	6.2	7.1	
Coleoptera	1 1	1 6	17 5	8 8	3 3	1 5	5 1	3 9	1 2	.7	2.5		5.7	1.5	3 0	
Neuroptera	7		4	1 4	3											
Trichoptera	8 2	2 8	1 7	12 0	1 2	6	1 2	1 0	2	2.5	1.9			9	1.7	
Lepidoptera				3		1	23 3			.3	1			1.4	5	
Diptera	26 4	49 9	29 7	26.4	15 1	15 5	34 5	24 2	26 9	72 0	54 4		13 5	77.2	72 2	
Hymenoptera					3	1	2.5	1.1		1 0	1			1 8	1 9	
Other	2	4	6	3		.1	1.2	.4	7	1			.7	1 5	6	

1. Other is the sum of all taxa that did not comprise more than 1 percent of the total number of organisms within that season

2. Number of organisms and sample weights

Parameter	Benthic				Drift				Sticky				Water			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Number of samples	16	32	50	47	8	14	22	21		15	21	22		10	11	16
Mean number of organisms per sample	91 6	121 4	137 9	278.6	42.1	221.7	63 8	393 9		40.1	280.7	98.1		80.3	653.6	138 3
Minimum number of organisms per sample	6	1	1	12	6	11	5	2		5	18	17		1	130	5
Maximum number of organisms per sample	356	459	526	1174	120	1125	501	3859		152	979	282		513	1770	336
Mean sample weight(g)	264	.052	.106	.355	.043	.043	.300	.074						.026	.299	.076
Minimum sample weight(g)	.003	.000	.001	.012	005	.004	000	.003						001	.021	.004
Maximum sample	2 697	.248	1.121	2.318	180	.185	3.525	503						067	.720	.166

Porter, Pamela E.; Meehan, William R. Seasonal species composition of invertebrates in several Oregon streams. Res. Pap. PNW-RP-382. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station; **1987.** 36 p.

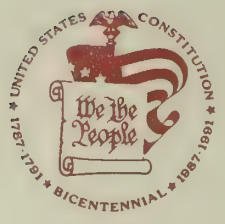
The invertebrate communities of eight Oregon streams were sampled seasonally from 1974 to 1976. Benthic, drift, and two types of aerial-trap samples were collected. Occurrence and percentage composition are summarized by sample type, season, and geographic area (coastal, Cascade, central, and eastern Oregon). Within 276 families, 426 taxa were identified; the 20 families most prevalent within each sample type accounted for the majority of organisms collected (77.8-91.8 percent). In most areas and seasons, Diptera and Ephemeroptera together comprised over half of the invertebrates collected.

Keywords: Invertebrata, aquatic life, Oregon.

The **Forest Service** of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing Nation.

The U.S. Department of Agriculture is an Equal Opportunity Employer. Applicants for all Department programs will be given equal consideration without regard to age, race, color, sex, religion, or national origin.

Pacific Northwest Research Station
319 S.W. Pine St.
P.O. Box 3890
Portland, Oregon 97208



December 1987

U.S. Department of Agriculture
Pacific Northwest Research Station
319 S.W. Pine Street
P.O. Box 3890
Portland, Oregon 97208

BULK RATE
POSTAGE +
FEES PAID
USDA-FS
PERMIT No. G-

Official Business
Penalty for Private Use, $300

do NOT detach label

United States
Department of
Agriculture

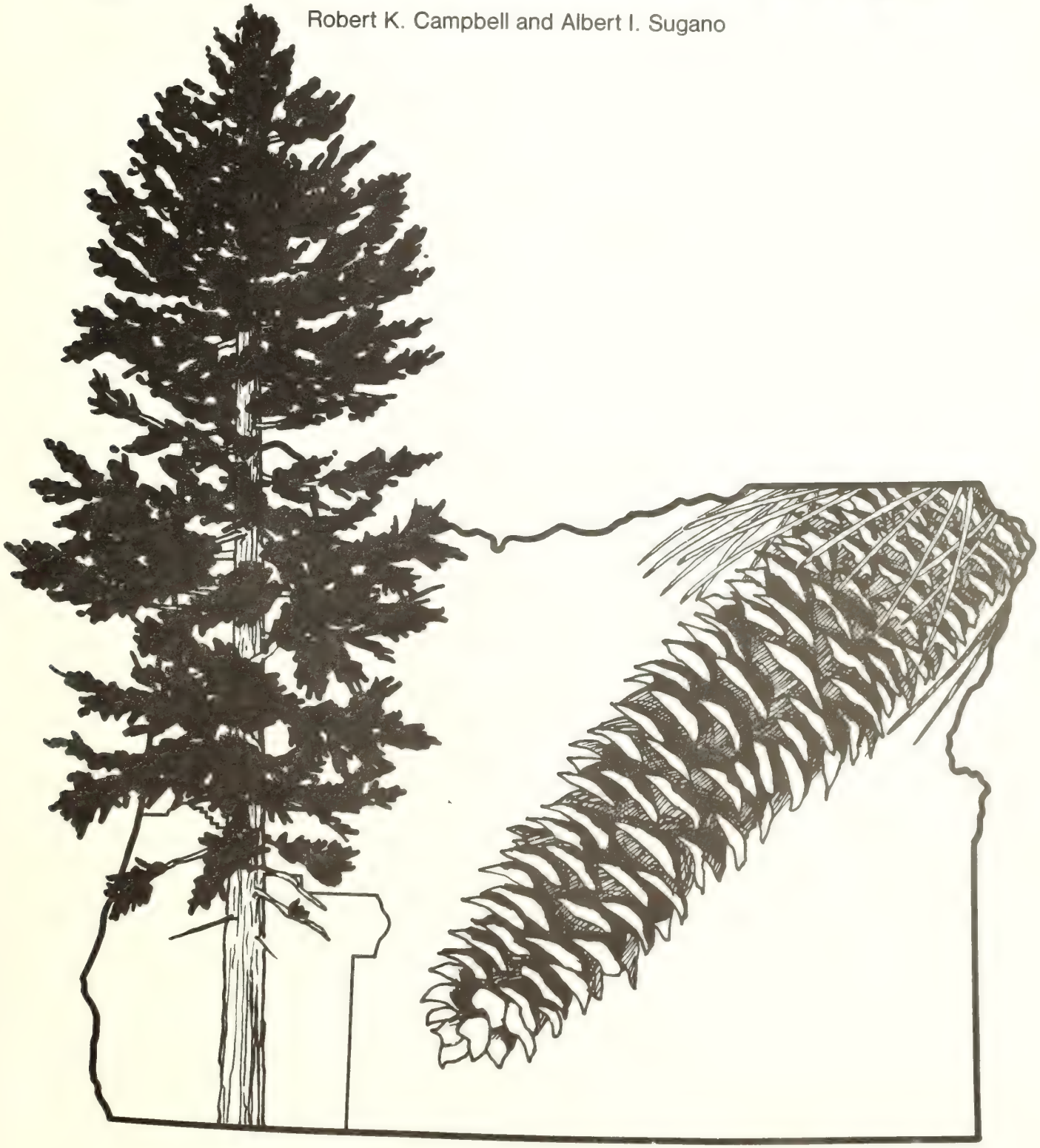
Forest Service

Pacific Northwest
Research Station

Research Paper
PNW-RP-383

Seed Zones and Breeding Zones for Sugar Pine in Southwestern Oregon

Robert K. Campbell and Albert I. Sugano



Authors

ROBERT K. CAMPBELL is a research geneticist and ALBERT I. SUGANO is a forester, Pacific Northwest Research Station, Forestry Sciences Laboratory, 3200 Jefferson Way, Corvallis, Oregon 97331.

Abstract

Campbell, Robert K.; Sugano, Albert I. Seed zones and breeding zones for sugar pine in southwestern Oregon. Res. Pap. PNW-RP-383. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station; **1987.** 18 p.

Provisional seed zones and breeding zones were developed for sugar pine (*Pinus lambertiana* Dougl.) in southwestern Oregon. Zones are based on a map of genetic variation patterns obtained by evaluating genotypes of trees from 142 locations in the region. Genotypes controlling growth vigor and growth rhythm were assessed in a common garden. Within southwestern Oregon, two zones are recommended for low elevations ($<$ 740 m), two zones for middle elevations ($>$ 740 and $<$ 1172 m), and four zones for high elevations ($>$ 1172 m).

Keywords: Seed zones, geographic variation, genetic variation, adaptation (plant), sugar pine, *Pinus lambertiana*.

Summary

The zones presently used to guide seed transfer and breeding of sugar pine in southwestern Oregon are derived from a map prepared by the Western Forest Tree Seed Council in 1966. The council members attempted to classify the region into zones of homogeneous environment based on information from local foresters about climate, growth potential, and growth habit of indigenous tree species, primarily Douglas-fir. Seed zones ideally should be based on knowledge of the long-term effects of seed transfer; information about the genetic structure and habitat of the species is a less satisfactory base. Neither kind of information was available for sugar pine when the seed zone map was made in the early 1960's.

Satisfactory data about effects of seed transfer can come only from field tests carried to rotation age, but such tests are generally not affordable. An alternative to the long-term field test is to map genetic variation patterns as they exist in the native stands. Such a map can be used to devise provisional zones.

This paper reports new seed-transfer zones based on genetic variation patterns for sugar pine in southwestern Oregon. Seedling progeny from 200 trees from 142 locations in southwestern Oregon were grown as families in a common-garden nursery to evaluate the genotypes of the parents. Genetic variation among the families indicated that two principal components of genetic expression in several traits could be used to describe adaptive differences among populations. For each component, the variability among local populations accounted for about 50 percent of genetic variability among all families. The remaining 50 percent of genetic variation was contributed by families within local populations. Natural selection apparently has created local populations in the region that vary genetically in complex patterns along complex environmental gradients.

The zones developed from the genetic variation patterns differed greatly from the zones recommended in the Forest Tree Seed Council map. If a zone is considered as having boundaries of latitude, east-west departure, and elevation, the new zones are larger in all three dimensions. In southwestern Oregon, two of the new zones were recommended at low elevations ($<$ 740 m), two at middle elevations ($>$ 740 and $<$ 1172 m), and four at high elevations ($>$ 1172 m).

Risks of poor adaptation, which were estimated by simulated transfers within a zone, suggested that in the average seed transfer within zones, fewer than 25 percent of seedlings were likely to be poorly adapted. The estimates of risk applied only to transfers among sugar pine sites within the zone. Zones for Douglas-fir or for other species may be greatly different in size and configuration.

Contents

1 **Introduction**

1 **Materials and Methods**

5 **Results**

14 **Discussion**

17 **Acknowledgments**

17 **English Equivalents**

17 **Literature Cited**

Introduction

The seed transfer and breeding zones that foresters and tree breeders use to restrict transfer of sugar pine (*Pinus lambertiana* Dougl.) in southwestern Oregon are derived from a seed zone map prepared by the Western Forest Tree Seed Council (Oregon [Tree Seed Zone] 1966). Although seed zones should reflect the habitat and genetic structure of the species, such information was not available in 1966 when the map was prepared. The scientific basis of zone maps for sugar pine therefore required evaluation.

Field tests are needed that evaluate performance to rotation age to define zones precisely. In the absence of other knowledge, a design that samples many seed sources and many plantation sites within the region is necessary. With anything less, results cannot be extrapolated from the test sites to the commercial sites, and zone boundaries cannot be objectively drawn. Experiments of this scale are generally unaffordable.

An alternative to extensive, long-term field testing is to map patterns of genetic variation in the native stand from short-term tests at a single site (Campbell 1986, Langlet 1945, Rehfeldt 1983, Squillace 1966). Two main assumptions are implicit if genetic maps are used to devise provisional zones: (1) genetic variation among populations reflects natural selection by an environment that varies across locations; and (2) the greater the genetic difference among populations, the greater the risk in transfers of seedlings between origins of populations. Other assumptions of this model for devising seed-transfer guidelines are discussed elsewhere (Campbell 1986). Maps can also provide a framework for sampling seed sources and plantation sites so that few long-term tests are needed to validate zone boundaries.

This paper reports the mapping of genetic variation of sugar pine in southwestern Oregon and the provisional seed zones and breeding zones derived from the map.

Materials and Methods

Cones were collected from 2 trees at 58 locations and 1 tree at an additional 84 locations for a total of 200 trees at 142 locations. The area of sampling extended north from the California-Oregon border to the latitudes of Sutherlin, Oregon (T. 25 S.), in the Cascade Range (160 km) and Cape Blanco (T. 32 S.) in the Siskiyou Mountains (90 km). The region ranged west to east from near the Pacific Ocean to the crest of the Cascade Range (R. 4 E., 170 km).

Besides the areal dimensions, seven other variables were measured to index the habitat of each tree.

1. Elevation, ranging from 300 to 1600 m but, for frequency of occurrence within elevational classes, uniformly distributed between 600 and 1400 m.

2. Aspect, uniformly distributed from 0° to 360°.

3. Slope, uniformly distributed from 0 to 65 percent.

4. Drainage direction, which might index fog propensity within the region, uniformly distributed from 0° to 360°.

5. Mean annual precipitation (Froehlich and others 1982), ranging from 73.7 to 355.6 cm and distributed with two peaks, one with a mean of 124.5 cm and the other with a mean of 289.6 cm.

6. Horizon sum, an index of general exposure, calculated as the sum of the vertical angles from the parent tree to the horizon taken at 22.5° intervals of azimuth from 0° to 360°. The sums ranged from 0 to 472 but were concentrated between 120 and 285.

7. Sun exposure on April 3, taken as the vertical angles at intervals of 22.5° east (90°) to west (270°) and plotted to provide a graph of the horizon across the southern sky. The minutes of direct sun exposure at the tree location were calculated by using this graph and the graphed path of the sun angle throughout the day of April 3; values ranged from 400 to 764 minutes with a median of 690 minutes.

We estimated genotypic values of parent trees by growing their families from open-pollinated seeds in seed germinators and in a common garden. For each of the 200 trees, seeds were separated into two 50-seed lots. We started stratification (130 days at 1.7 °C) and germination for one lot a week before the other lot to provide two replications. Lots were germinated in petri dishes at 22 °C and 14-hour days. Germinated seeds were counted daily to obtain the mean and standard deviation of germination rate (Campbell and Sorensen 1979). Germinated seeds removed during daily counts were stored at 1 °C for outplanting later in the common-garden test.

Germinated seeds from each of the 200 families were planted in four replications of four-seedling row plots in each of four nursery beds. The original plan was to impose different growth treatments on the four nursery beds. This was precluded soon after planting by an unidentified damping-off disease that caused mortality averaging 40 percent in two beds and 60 percent in the other two. We therefore attempted only two test environments: a control with no treatment for the two beds with greatest mortality and a warm soil and warm air treatment for the two beds with least mortality. We created warm soil by burying heating cables 15 cm below the soil surface. Warm air was obtained by covering beds with a polyethylene tent; this was done only in spring and autumn to extend the growing season. Temperature was not measured, but our experience with similar treatments suggests that the temperature in growth zones probably exceeded the ambient by 0 to 10 °C, depending on cloud cover and time of year.

Ideally, traits measured in the common garden should be suitable for evaluating differences in vigor and timing of growth among families. In sugar pine, determining stop and start of the vegetative cycle by "bud-burst" and "bud-set" is difficult. We anticipated, however, that differences in growth rhythm would show in the structure of genetic correlations among different segments of height extension, each segment considered as a separate trait. In the second growing season, seedling height was therefore measured 10 times, 3 to 7 days apart, (table 1), from the beginning of the extension period in April to the end in late May. In the third growing season, height was measured three times from May 25, shortly after the start of extension, to June 17, after extension had ceased. Diameter was measured once at the end of the third growing season.

The mortality in the first growing season caused drastic changes to parts of the intended analyses, and some pooling of data was necessary. We eliminated the designed replication within beds by treating seedlings within families as if they were randomly allocated rather than as being planted in row plots. Two replications were created by considering the two beds in each treatment as two blocks.

Table 1—Trait code, dates, and units of measurement of seedling traits; total height (HT), total diameter (DIA), mean germination rate of 50 seeds (DR MN), and standard deviation of germination rate (DR SD)

Code	Date measured	Measurement units
HT 21[1/]	April 4-6	cm
HT 22	April 9-10	cm
HT 23	April 12-13	cm
HT 24	April 19-21	cm
HT 25	April 23-26	cm
HT 26	April 28-30	cm
HT 27	May 3-7	cm
HT 28	May 10-12	cm
HT 29	May 17-19	cm
HT 21	May 24-26	cm
HT 31	May 25-27	cm
HT 32	June 7-9	cm
HT 33	June 15-17	cm
DIA 31	December 15-22	mm
DR MN	April 13-30	(days to germination) $^{-1}$
DR SD	April 13-30	(days to germination) $^{-1}$

[1/] The 1st numeral in the code designates the growing season, the 2d the place in sequence of measurements; for example, HT32 is the 2d measurement of total height in the 3d growing season.

Analyses of data from the two beds in the control treatment indicated that for most traits the within-plot variation was so large and the genetic variation so small that analyses did not help in evaluating genotypes. Analysis of the control treatment was discontinued.

The analyses of data from the warm treatment proceeded in nine steps. Seven are described in detail elsewhere (Campbell 1986) and are listed here only as a summary.

1. Analyze variance and covariance (table 2).

2. Calculate genetic correlation coefficients at the source and family within source (hereafter family) levels.

3. Reduce the dimensions in the data by a principal component analysis of the matrix of coefficients from the source level of genetic correlation.

4. For each of the significant principal components, calculate factor scores for each source and family.

Table 2—The partition of variation among seedlings into sources of variation, and the expected mean squares used in estimating components of variance

Source of variation	Degrees of freedom	Expected mean squares [1]
Total	3,647	
Replications	1	
Sources	141	$\sigma^2_w + 18.20\ \sigma^2_{f(s)} + 25.66\ \sigma^2_s$
Families in sources	58	$\sigma^2_w + 18.20\ \sigma^2_{f(s)}$
Within plots	3,447	σ^2_w

[1] σ^2_s = variance of seed-source effects;

$\sigma^2_{f(s)}$ = variance of effects of families within seed source; and

σ^2_w = variance of within-plot effects.

5. Describe the pattern of genetic variation in factor scores for each principal component by a regression analysis (backward stepwise, Draper and Smith 1966) that uses indices of the parent-tree habitat as predicting variables. The preliminary model included quadratic and interaction terms suggested by previous experience (Campbell 1979, 1986) for some variables in addition to linear terms for all variables.

6. Calculate lack of fit using variation among families at a location as pure error (Draper and Smith 1966).

7. Calculate an index of risk in seed transfer—risk is the fraction of non-overlap between factor-score distributions for native and introduced seed sources.

We added two other steps, a cluster analysis and a new procedure for assigning boundaries to seed zones. The first was tried because of significant lack of fit to the regression model. We thought the second was needed because a change from previous procedures (Campbell 1986) would make the resulting seed zones more easily used by foresters.

Lack of fit could not be rectified by common procedures. Therefore, in addition to scattergrams of residuals with location variables (Draper and Smith 1966), deviations from the models were clustered using McIntire's (1973) algorithm and computer program (MACLUS, Computer Center, Oregon State University). Though unlikely, deviations might vary jointly in patterns not otherwise obvious in the residuals.

The second new step was a procedure to provide zones with boundaries determined only by the customary geographic and elevational limitations. The resulting zones were somewhat larger than zones developed in strict compliance with genetic variation patterns, but they should be easier to use in practice. The procedure had five parts.

1. On a map, pinpoint locations at low, middle, and high elevations in each township (9.65 by 9.65 km) within the region.

2. Record all pertinent habitat variables at each of 629 locations.

3. Use the regression equations for describing genetic variation patterns to calculate factor scores at each location.

4. Divide the region into tentative zones based on visual inspection of genetic variation patterns.

5. Calculate risk values (Campbell 1986) for 200 hypothetical transfers between randomly chosen pairs of locations within each tentative zone.

Steps 4 and 5 were repeated until zones were defined in which fewer than 5 percent of the simulated transfers created risks greater than 0.5. The average risk associated with seed transfers within zones was less than 0.25. Within such zones, about 25 percent of the seedlings planted are expected to be poorly adapted in comparison to the indigenous seedlings.

Results

We partitioned variation among seedlings into effects of seed sources (σ^2_s), families in sources ($\sigma^2_{f(s)}$), and variation within plots (σ^2_w), which included variation within rows and among rows in beds. With one exception (standard deviation of germination rate of seeds), all traits differed among sources and families. In the second growing season, an average of 6.0 percent of the variance in height traits could be attributed to source, 7.9 percent to families, and 86.1 percent to within-plot (table 3). In the third growing season, more of the average variance in height and diameter was found among sources (10.2 percent) and less among families (6.1 percent) and within plots (83.7 percent). Throughout the third growing season, variation among sources increased steadily and variation among families and within plots decreased steadily (table 3). This apparent trend was based on only three measurement periods, which sampled early, middle, and late phases of extension growth.

The largest part of the variation among seedlings occurred within plots; some was the result of genetic variation among individuals within a family. For this paper, the genetic variation within plots was assumed to be two-thirds of the additive genetic variance. Sugar pine usually grows in isolated, small stands where pollination probably includes selfing or crossing between near relatives. The genetic correlation among family members is therefore probably nearer to 0.33 than to 0.25. Given a correlation of 0.33, the additive genetic variance (σ^2_A) is 3 $\sigma^2_{f(s)}$ 2 and the amount within plots is 2 $\sigma^2_{f(s)}$, that is:

$$\sigma^2_A - \sigma^2_{f(s} - 2\,\sigma^2_{f(s)} .$$

Table 3—Analysis of variance of traits and of factor scores of principal components (PC-1 and PC-2)

Trait[1]	Mean	Total variance[2]	Percentage of total variance			
			Among sources	Among families	Within families	Among plots
HT 21	7.22	3.197	6.9**	8.2**	84.9	
HT 22	9.20	4.169	7.4**	7.4**	85.2	
HT 23	9.69	4.710	5.7*	8.4**	85.9	
HT 24	10.25	5.318	6.1**	7.2**	86.6	
HT 25	10.90	6.331	5.2*	7.6**	87.2	
HT 26	11.79	7.496	5.2*	7.8**	87.1	
HT 27	12.35	8.668	5.3*	8.1**	86.7	
HT 28	12.89	9.317	5.4*	7.7**	87.0	
HT 29	13.48	10.567	6.5**	8.2**	85.3	
HT 210	13.45	10.597	6.3*	8.3**	85.4	
HT 31	18.14	21.964	8.8**	8.6**	82.6	
HT 32	37.62	77.958	11.6**	6.1**	82.4	
HT 33	39.92	77.390	12.8**	5.4**	81.9	
DIA 31	10.06	4.290	7.7**	4.4**	87.9	
DR MN	.38	.055	48.4**	8.9*		42.8
DR SD	.24	.020	38.3*	8.0		53.7
PC-1	15.70	12.833	10.2**	8.6**	81.2[3]	
PC-2	2.50	3.153	27.8**	28.3**	44.0[3]	

* = $0.05 < P > 0.01$; ** = $P < 0.01$

[1] Trait code and measurement units as in table 1.

[2] Total variance for HT, DIA, PC-1 and PC-2 is among-source variance (σ^2_s) + among-family variance ($\sigma^2_{f(s)}$) + within-family variance (σ^2_w). Total variance for seed traits is $\sigma^2_s + \sigma^2_{f(s)} + \sigma^2_p$ where σ^2_p represents variance of plot effects.

[3] In calculating factor scores for individual seedlings, seed traits were taken as having no variation within plots.

For the 10 height traits in the second growing season, this additive variance represented an average of 18.2 percent of within-plot variance. The additive genetic variance within plots decreased from 21 percent to 15 percent to 13 percent of within-plot variance in the three successive height measurements of the third growing season. The remaining variation was nonadditive genetic variation and environmental variation. Variable spacing among seedlings caused by first-year mortality probably contributed to the large size of the nongenetic variation.

When genetic correlations were calculated among growth traits, those calculated at the source level of variation were about 50 percent larger than those at the family level (table 4). At the source level, some coefficients were larger than one. We could not determine whether this was caused by an underestimate of genetic variance or by an inflation of covariance because of unclassified elements of common environment.

Table 4—Genetic correlation coefficients; above diagonal for seed sources, below diagonal for families

Trait	HT 21	HT 25	HT 210	HT 31	HT 32	HT 33	DIA 3	DR MN	DR SD
HT 21		0.920	0.845	1.026	0.890	0.917	1.049	0.474	0.155
HT 25	0.769		.988	.973	.982	.963	.986	.700	.396
HT 210	.855	893		1.004	1.056	1.054	1.031	.555	.390
HT 31	.386	.653	.621		.962	.948	.908	.427	.123
HT 32	.331	.531	.623	.810		1.009	.999	.136	.034
HT 33	.311	.568	.633	.923	.965		.960	.170	.005
DIA 3	.140	.438	.574	.853	.853	.912		.125	.047
DR MN	-.583	-.664	-.715	-.413	-.356	-.410	-.263		1.167
DR SD	-.361	-.434	-.560	-.141	-.319	-.268	-.248	.595	

Correlations between seed and growth traits at the source level were uniformly positive, and those at the family level were uniformly negative (table 4). Larger heights and diameters of seedlings were associated with faster rates of germination of seeds at the source level but with slower rates at the family level. Consistently more variation was found among individual seeds within those lots with faster mean germination rates. This correlation was stronger at the source level than at the family level.

To simplify interpretation of genetic variation patterns, the intercorrelated growth and seed traits were reduced to fewer dimensions by principal component analysis. The genetic correlation matrix at the source level was used as input. The correlation matrices at source and family level were different and the adaptational problems connected with seed transfer were probably more closely connected with source variation than with family variation.

The first two principal components explained about 95 percent of the variation in all traits (table 5). The first component (eigenvalue 14.076) explained six times as much of the variation as did the second component (eigenvalue 2.195). Loadings indicated that factor scores of the first principal component (PC-1) were larger in families with a larger final stem diameter and in families that were taller at all measurement periods. Larger factor scores in the second principal component (PC-2) mainly reflected large mean germination rates of seed and larger variation in rates among seeds (table 5). But factor scores for PC-2 were also larger when seedlings were larger at some periods of the second growing season (for example, traits 23, 25, 28) and smaller if seedlings were larger at other periods (for example, traits 21, 24, 26). The second principal component therefore also may reflect a pattern of extension growth that was quasi-sinusoidal within the growing season and different among sources.

Table 5—The two main principal components (PC), their loadings with traits, the variance of their factor scores (eigenvalue), and their contribution in explaining variation among all traits (as a percentage)

Trait	PC-1[1/]	PC-2[2/]
HT 21	0.934	-0.109
HT 22	.970	-.023
HT 23	.990	.025
HT 24	.987	-.034
HT 25	1.002	.108
HT 26	.992	-.066
HT 27	1.019	.058
HT 28	1.018	.124
HT 29	.999	.068
HT 210	1.003	.016
HT 31	.980	-.122
HT 32	.979	-.300
HT 33	.975	-.294
DIA 3	.988	-.296
DR MN	.541	.940
DR SD	.308	.990

[1/] Eigenvalue, 14.076; percentage of total variation, 82.6.

[2/] Eigenvalue, 2.195; percentage of total variation, 12.9.

The factor scores (PC-1 and PC-2) varied significantly ($P < 0.01$) among sources and families in sources (table 3). The variance among sources (σ^2_s) accounted for 54 percent of the total variance among all families ($\sigma^2_s + \sigma^2_{f(s)}$) in PC-1. This variability among all families represented, in turn, 19 percent of the variation in PC-1 among all seedlings. Sources accounted for 49 percent of variance among all families in factor scores of PC-2. An unbiased estimate of the percentage of variation in PCs among seedlings within plots was not possible. Because seed traits were measured in germinators rather than in the cold-frame plots, seed traits had to be treated as having no variation within plots in calculating factor scores. The within-family variations in factor scores therefore does not include a contribution from within-family variation in seed traits. The estimate of within-family variance is affected very little for PC-1 but greatly for PC-2 (table 3).

Differences among sources were only partly associated with habitat variables at the source origin. Regression equations relating factor scores of families to habitat variables explained 31 and 26 percent of sums of squares for PC-1 and PC-2, respectively. A large part of the remaining "unexplained" variability resulted from the large difference in factor scores between the two trees sampled at 58 of the 142 locations. Even after taking this into account, though, there was still significant lack of fit to the equation (table 6). For the occurrence of lack of fit to have been judged nonsignificant (for example, lack of fit, $P > 0.10$), the respective equations for PC-1 and PC-2 would have had to account for at least 39 and 36 percent of the sums of squares.

Table 6—Regression analyses of factor scores from principal components

Principal component 1				Principal component 2			
Variable[1]	Partial coefficient	Significance P<....	Standardized coefficient	Variable[1]	Partial coefficient	Significance P<....	Standardized coefficient
D	0.3986E-01	0 000	1.16	LDE	-0 8384E-06	0 000	-0 63
E	-.5959E-02	000	-1.00	DA	-.3223E-02	045	-.13
D^2	-.2478E-03	.000	-.96	D	-.1106E-01	.000	-.43
DE	.7132E-04	.001	.93	LE	.7475E-04	000	.62
EDR	-.94879E-06	011	-.58	CONST	3 0765	.000	
ER	4918E-04	013	.53				
CONST	14.9006	000					

Probability of lack of fit for PC-1 is 0.024; R^2 = 0.31

Probability of lack of fit for PC-2 is 0.020; R^2 = 0.26

[1]/ Where: E = elevation in meters (-1,000);
L = distance south to north in kilometers (-4,700) taken from Geological Survey maps (Oregon [Topographic] 1976),
D = distance west to east in kilometers (-425) from above maps,
R = annual precipitation in inches (2 54 cm) from Froehlich and others (1982),
A = aspect in cosine (degree azimuth); and
CONST = constant.

Residuals from the equations were examined in attempts to eliminate lack of fit. The residuals represented deviations from the regression equation of genotypic values of 200 parent trees, including the pairs of trees from 58 locations. Each tree had two genotypic values (and residuals), the factor scores of PC-1 and PC-2.

Conventional methods for examining residuals (Draper and Smith 1966) did not reveal patterns in the deviations. We therefore used cluster analysis to determine if homogenous groups of deviations were contributed by trees that were also homogenous in some identifiable aspect of their habitats. During clustering, the pooled within-group sums of squares decreased steadily when observations were factored into smaller and smaller groups until a minimum was reached when about 20 clusters had been formed.

The 20 clusters were homogenous in characteristics of factor scores within clusters but were extremely heterogenous in the origin of trees. Only 6 of the 58 pairs of trees were found together within clusters, 1 pair in each of 6 different clusters. Individuals within clusters commonly were from widely scattered locations within the region. On other occasions, trees from two clusters that were greatly different in the size and sign of the included deviations might be of similar origin. The deviations were therefore not patterned in any predictable manner, in respect to either the apparent relation among trees or the origins of trees. The significant lack of fit indicated that groupings of deviations of PC-1 or PC-2 should be expected. Apparently these groups were not connected with one another or with any readily identifiable features of the habitat of parent trees.

Predictions from regression equations indicated that variation in PC-1 was associated with the annual precipitation, elevation, and distance from the ocean of the origin of parent trees. Factor scores for trees at lowest elevations were smaller in areas of highest precipitation nearest the ocean and in areas of lowest precipitation farthest from the ocean (fig. 1A). The trend with precipitation was reversed for trees at highest elevations; factor scores were smallest in areas of lowest precipitation nearest the ocean and in areas of highest precipitation farthest from the ocean (fig. 1D). Very little genetic variation existed among trees in a broad central band of elevations (fig. 1, B and C). Within this band, factor scores were slightly smaller in the western part of the region.

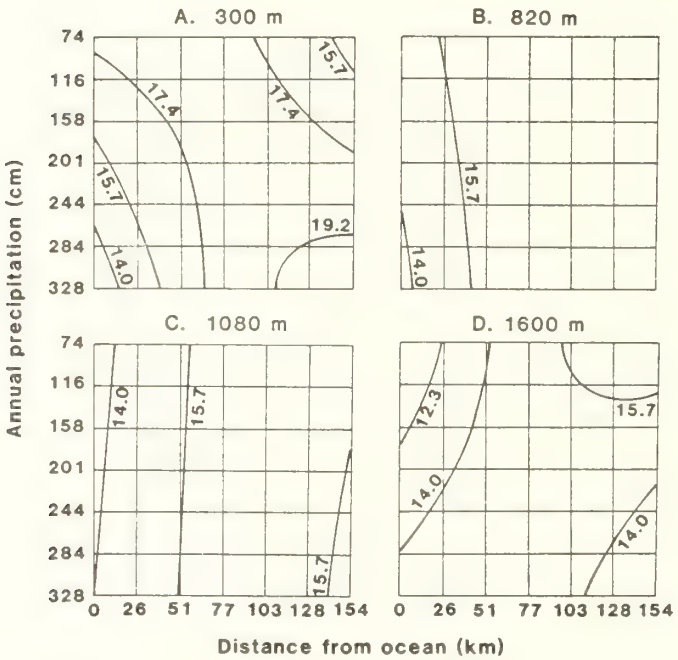


Figure 1—Factor scores (isolines are labeled with score values) of the first principal component: (A) sites at 300 m, (B) sites at 820 m, (C) sites at 1080 m, and (D) sites at 1600 m.

Trees differed in PC-2 depending on elevation, latitude, and distance of trees from the ocean. Factor scores of trees at lowest elevations were smallest in the central part of the region and largest toward the southeast and northwest (fig. 2A). Some fairly steep gradients exist from north to south in the western part of the region. For trees at the highest elevations, factor scores were smallest in the southwest and northeast and largest in the northwest. The gradient was therefore found in the western part of the region (fig. 2D). With PC-2, as with PC-1, little genetic variation was found among trees throughout the region within a broad intermediate band of elevations. Within this band, the largest scores were found in the west (fig. 2, B and C).

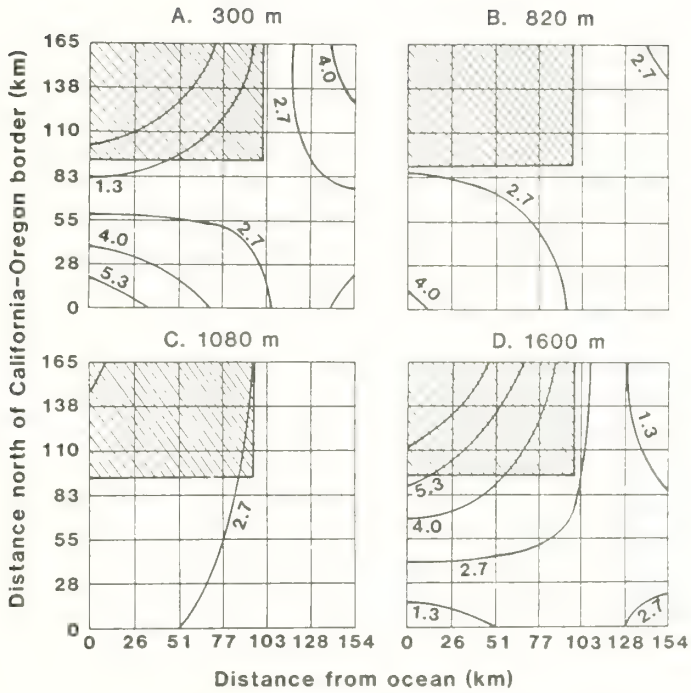


Figure 2—Factor scores (isolines are labled with score values) of the second principal component: (A) sites at 300 m, (B) sites at 820 m, (C) sites at 1080 m, and (D) sites at 1600 m. Sites in the hatched area were sampled minimally or not at all.

Creating eight zones divided southwestern Oregon into areas in which fewer than 5 percent of transfers involved risks greater than 0.5 (table 7). Two zones were needed for low elevations ($<$ 740 m), two for middle elevations ($>$ 740 m and $<$ 1172 m), and four for high elevations ($>$ 1172 m). The average transfer within a zone had a risk of $<$ 0.25, and only about 2 percent of transfers had risks greater than 0.5. The distribution of risks of hypothetical transfers within zones was typically bell shaped with a slight positive skew (fig. 3). The boundary between the east and west zones at low elevations (fig. 4) fell on the isohyetal line of 152 cm of annual precipitation, which wanders north and south primarily within the townships in R. 8 W. (Froehlich and others 1982). For practical reasons, and because practical and biological objectives coincided, other borders were placed along major highways within the region (fig. 5 and 6).

Table 7—Statistics of predicted risks in 200 simulated transfers within each of the 8 provisional seed and breeding zones

Zone[1/]		Transfer risk		Percentage of transfers with risks greater than indicated[2/]	
		Average	Maximum		
				Percent	$> M_i$
Low 1	(< 740 m)	0.245	0.600	2	0.493
Low 2	(< 740 m)	.241	.628	2	.516
Middle 1	(> 740 m and < 1172 m)	.213	.582	1	.479
Middle 2	(> 740 m and < 1172 m)	.156	.423	0	.423
High 1	(> 1172 m)	.133	.450	0	.450
High 2	(> 1172 m)	.198	.619	2	.509
High 3	(> 1172 m)	.227	.569	2	.508
High 4	(> 1172 m)	.189	.618	1	.508

[1/] See figures 4, 5, and 6 for locations of zones.

[2/] By the mismatch index (M) in the i^{th} zone; for example, if i = low 1, then 2 percent of 200 simulated transfers in low 1 had predicted risks greater than M = 0.493.

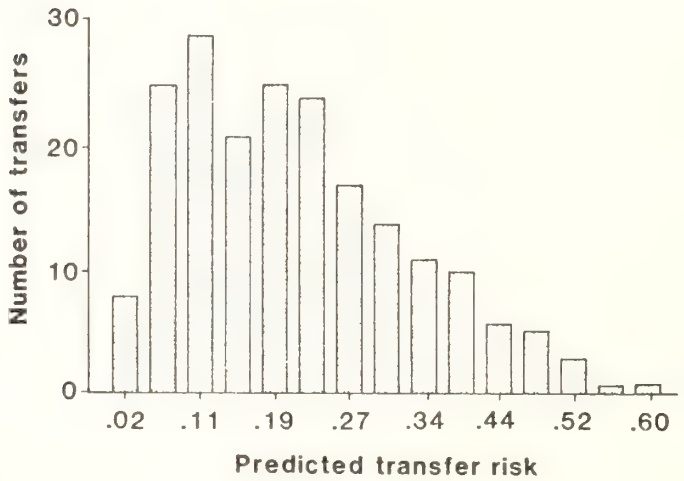


Figure 3—Distribution of variation in predicted risks for 200 hypothetical transfers within midelevation zone 1.

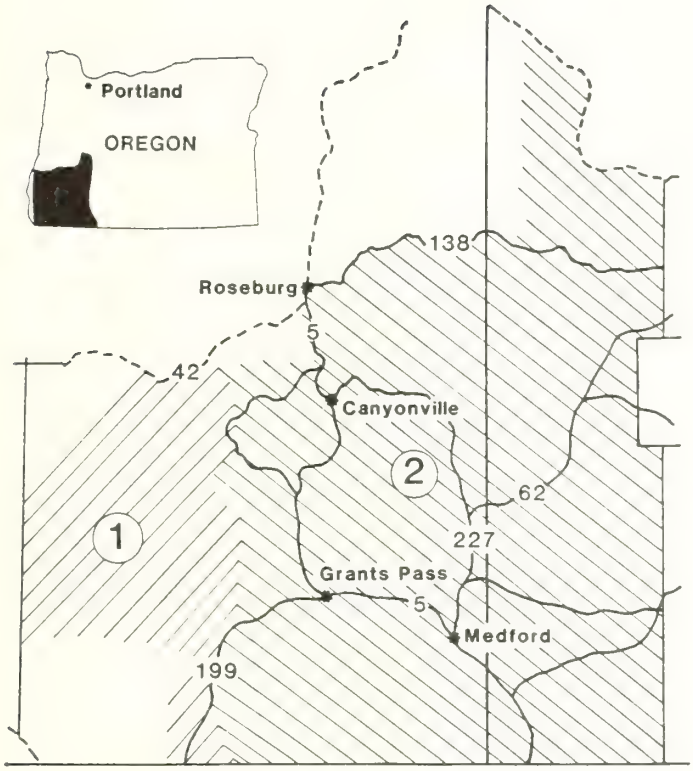


Figure 4—Provisional seed-transfer and breeding zones for sugar pine at low elevations (< 740 m). Zones 1 and 2 are designated by diagonal hatching with lines in zone 1 running perpendicular to lines in zone 2. The small numbers 5, 42, 62, etc., refer to Federal and State highways within southwestern Oregon.

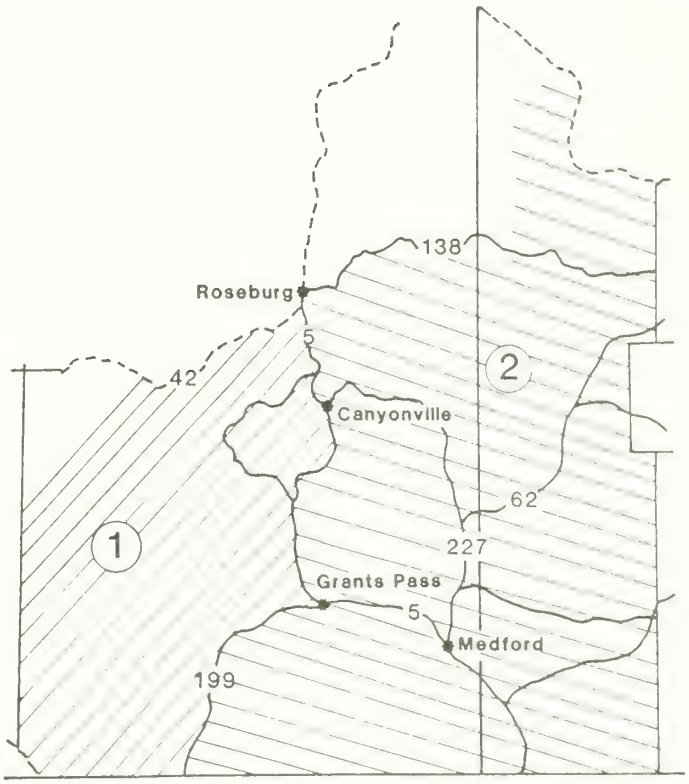


Figure 5—Provisional seed-transfer and breeding zone for sugar pines at middle elevations (> 740 m and < 1172 m). Zones 1 and 2 are designated by diagonal hatching with lines in zone 1 running perpendicular to lines in zone 2. The small numbers 5, 42, 62, etc., refer to Federal and State highways within southwestern Oregon.

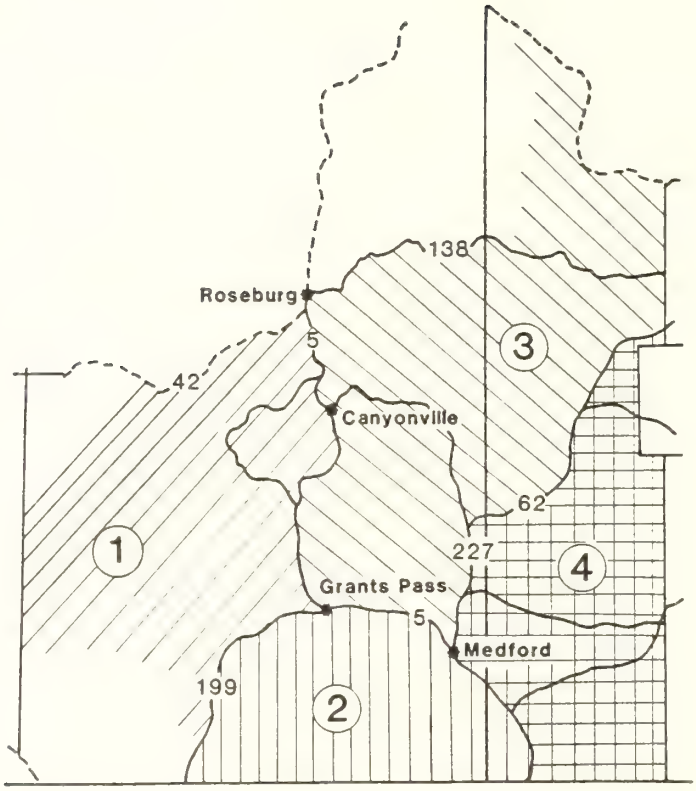


Figure 6—Provisional seed-transfer and breeding zones for sugar pines at high elevations (> 1172 m). Zones 1 to 4 are designated by hatchings of different types. The small numbers 5, 42, 62, etc., refer to Federal and State highways within southwestern Oregon.

Discussion

The dimensions of the seed zones we recommend depend on a particular conceptual model of the relation of adaptation and seed transfer. Assumptions and other features of the model are discussed elsewhere (Campbell 1986). Only those aspects relevant to limits of transfer are discussed here.

The basic tenet of this model is that only a proportion of any transferred group of seedlings will be well adapted in comparison to the adaptation of seedlings within the indigenous seed supply. Furthermore, well-adapted trees are assumed to be better able to use the resources and conditions of the site than are poorly adapted trees. Poorly adapted trees will therefore be less productive over an average of years, generations, and sites than will well-adapted trees.

If well-adapted trees are more productive than less well-adapted trees, then the distribution of adapted trees within a plantation is important. The best adapted trees should be distributed throughout the plantation. If we define a spacing subunit (for example, 4 by 4 m) as the area occupied by one crop tree, then ideally every spacing subunit should include at least one well-adapted tree.

The well-adapted seedlings in a transferred seedling lot cannot be identified at planting. Planting more seedlings per hectare is the only procedure available for increasing the probability that a well-adapted seedling will be planted in a spacing subunit. The larger the proportion of poorly adapted seedlings in a lot, the larger the number of seedlings needed per crop tree. The calculations of this number provided the basis for limiting seed transfer within seed zones in our study.

The probability of a well-adapted seedling being planted within a spacing subunit is less than one—a reasonable upper limit is P = 0.98. Hypothetically, this upper limit will ensure greatest site productivity but at the cost of planting several seedlings per crop tree. We assumed a maximum investment of five or six planted seedlings per crop tree.

The maximum investment dictates the maximum mismatch index (M) permissible within a seed zone. The maximum index is calculated from the relationship:

$$P = 1 - Q^{N/C};$$

where:

P = the probability of an adapted seedling being included in a spacing subunit, 0.98 in this case;
Q = 1 - S(1-T)(1-M);
N = the number of seedlings to be planted for a given number of crop trees per hectare (C);
C = crop trees per hectare;
S = the proportion of seedlings surviving the early establishment period;
T = the proportion of seedlings removed in early thinnings; and
M = the mismatch index—the proportion of planted seedlings that are poorly adapted relative to seedlings in the indigenous population.

Then, the number of seedlings required per hectare is:

$$N = \frac{\log (1-P)}{\log Q} C .$$

But for our purposes, the influence of early regeneration success and thinning was ignored, so S = 1, T = 0. Also, only the number of seedlings needed per crop tree (n) was of interest. Therefore:

$$n = \frac{\log (1-P)}{\log M} .$$

From this, if the maximum M is 0.50, the maximum number of seedlings invested per crop tree is 5.6.

One implication of the model is that any retreat from the maximum investment of seedlings per crop tree will reduce productivity. Calculations of this investment are more useful, however, as indicators of possibilities rather than as a prescription. Theoretical reasons have been given for not always expecting maximum productivity from the indigenous populations (Namkoong 1969). Other work (Braathe 1953) indicates that total harvest volume yield may not be greatly reduced by the patchiness in regeneration that could result from maladaptation, although the harvest quality may be considerably affected. Even if it is important that all crop trees are well adapted, economic reasons may demand planting fewer than 5.6 seedlings per crop tree. The average mismatch index, M, in the recommended zones was about 0.25; consequently, for the average transfer at M = 0.25, the planting of 2.8 seedlings per crop tree would ensure adapted crop trees. In these cases, planting more than 2.8 seedlings may be an unnecessary regeneration cost. These numbers assume complete success in regeneration and no early thinning; if either condition does not hold, the model indicates a larger number of seedlings per crop tree should be planted. Several items, other than adaptation, must be considered in any prescription for regeneration within seed zones.

How adequate the seed zones are will depend partly on how well the experiment fulfilled the assumptions the genetic mapping procedure was based on (Campbell 1986). Results from this experiment require three qualifications. First, the samples of locations were not evenly distributed throughout the region. Sugar pine tends to grow in small stands, which were more concentrated in the southwestern part of the region. More samples per unit area were taken in the southwest, so sampling tended to be proportional to the occurrence of the species rather than to area. Predictions from regression and therefore the delimitation of zone boundaries are more reliable for the western part of the region than for the eastern.

The second qualification results from problems encountered in growing seedlings in common gardens. Because of mortality, seedling genotypes were evaluated in only one environment. This limits the expression of gene effects in quantitative traits. Some genetic differences among sources may not have been manifested (Campbell and Sorensen 1978). If so, seed source variation has been incompletely characterized, and risks within zones may have been underestimated.

The third and most serious qualification is lack of fit to the regression model. A substantial amount of source variation was not accounted for by regression. Futhermore, the deviations from the model were not clustered in patterns related to geography of source origin. The source deviations could result from natural selection, but they could just as easily result from random genetic drift. If variation is caused by natural selection, risks within zones are underestimated. Making the zones smaller would not decrease the bias, however. The variation not accounted for by regression could not be ascribed to geography and therefore would not be reduced by making the zones smaller in any of the dimensions commonly used for seed-zone delimitation. Differentiation of populations by genetic drift is more likely in sugar pine then in many other species because sugar pine tends to be found in small, isolated stands. Variation caused by genetic drift should not affect zone boundaries because the differences among sources would not be predictable, adaptive differences.

The recommended zones are provisional. High seedling mortality in the common-garden test and lack of fit in the regression model have made this effort less satisfactory than it might have been. The delineation of zones did, however, incorporate all available quantitative information about genetic and habitat variation of sugar pine in southwestern Oregon. The zones, therefore, will minimize risks within the context of present information. But the information should be added to by other experiments and verified by long-term tests.

Acknowledgments

We thank Dave Van Den Berg, U.S. Department of the Interior, Bureau of Land Management, Medford, for assistance with cone collections. Financial support for this research was provided by the U.S. Department of the Interior, Bureau of Land Management, and the U.S. Department of Agriculture, Forest Service, under the auspices of the Southwest Oregon Forestry Intensified Research (FIR) Program.

English Equivalents

When given:	*Multiply by:*	*To find:*
Meters (m)	3.282	Feet
Kilometers (km)	0.621	Miles
Hectares (ha)	2.471	Acres
Celsius (°C)	1.8 (and add 32)	Fahrenheit (°F)

Literature Cited

Braathe, P. Undersøkelsen over utvikling av glissen gjenvekst av gran. Meddelelser fra det Norske Skogforsøksvesen. 12:298-301; **1953.**

Campbell, R.K. Mapped genetic variation of Douglas-fir to guide seed transfer in southwest Oregon. Silvae Genetica. 35:85-96; **1986.**

Campbell, R.K.; Sorensen, F.C. Effects of test environment on expression of clines and on delimitation of seed zones in Douglas-fir. Theoretical and Applied Genetics. 51:233-246; **1978.**

Campbell, Robert K. Genecology of Douglas-fir in a watershed in the Oregon Cascades. Ecology. 60:1036-1050; **1979.**

Campbell, Robert K.; Sorensen, Frank C. A new basis for characterizing germination. Journal of Seed Technology. 4:24-34; **1979.**

Draper, N.R.; Smith, H. Applied regression analysis. New York: John Wiley and Sons; **1966.** 407 p.

Froehlich, Henry A., McNabb, David H.; Gaweda, Frank. Average annual precipitation in southwest Oregon, 1960-1980. Oregon State University, Extension Service Miscellaneous Publication 8220, Corvallis; **1982.** 7 p.

Langlet, Olof. Om möjligheterna att skogsodla med gran-och tallfrö av orts-främande proveniens. Svenska Skogsförsanstalt. 1:68-79; **1945.**

McIntire, C.D. Diatom associations in Yaquina estuary, Oregon: a multivariate analysis. Journal of Phycology. 9:254-259; **1973.**

Namkoong, Gene. Nonoptimality of local races. In: Proceedings, Tenth Southern Conference on Forest Tree Improvement; 1969 June 17-19; Houston. College Station, Texas: Texas Forest Service, Texas A & M University; **1969;** 149-153.

Oregon [Tree Seed Zones]. Portland, Oregon: U.S. Department of Agriculture, Forest Service; **1966.** 1:500,00; Lambert conformed conic projection; colored.

Oregon [Topographic]. Denver, Colorado: U.S. Geological Survey; **1976.** 10,000-meter Universal Transverse Mercator Projection; zone 10, NK10-1, NK10-2.

Rehfeldt, G.E. Ecological adaptations in Douglas-fir (*Pseudotsuga menziesii* var. *glauca)* populations. III: Central Idaho. Canadian Journal of Forest Research. 13:626-632; **1983.**

Squillace, A.E. Geographic variation in slash pine. Forest Science. Monograph; **1966.** 56 p.

Campbell, Robert K.; Sugano, Albert I. Seed zones and breeding zones for sugar pine in southwestern Oregon. Res. Pap. PNW-RP-383. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station; **1987.** 18 p.

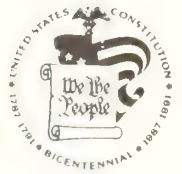
Provisional seed zones and breeding zones were developed for sugar pine (*Pinus lambertiana* Dougl.) in southwestern Oregon. Zones are based on a map of genetic variation patterns obtained by evaluating genotypes of trees from 142 locations in the region. Genotypes controlling growth vigor and growth rhythm were assessed in a common garden. Within southwestern Oregon, two zones are recommended for low elevations ($<$ 740 m), two zones for middle elevations ($>$ 740 and $<$ 1172 m), and four zones for high elevations ($>$ 1172 m).

Keywords: Seed zones, geographic variation, genetic variation, adaptation (plant), sugar pine, *Pinus lambertiana*.

The **Forest Service** of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing Nation.

The U.S. Department of Agriculture is an Equal Opportunity Employer. Applicants for all Department programs will be given equal consideration without regard to age, race, color, sex, religion, or national origin.

Pacific Northwest Research Station
319 S.W. Pine St.
P.O. Box 3890
Portland, Oregon 97208



July 1987

U.S. Department of Agriculture
Pacific Northwest Research Station
319 S.W. Pine Street
P.O. Box 3890
Portland, Oregon 97208

BULK RATE
POSTAGE +
FEES PAID
USDA-FS
PERMIT No. G-4

Official Business
Penalty for Private Use, $300

do NOT detach label

United States
Department of
Agriculture

Forest Service

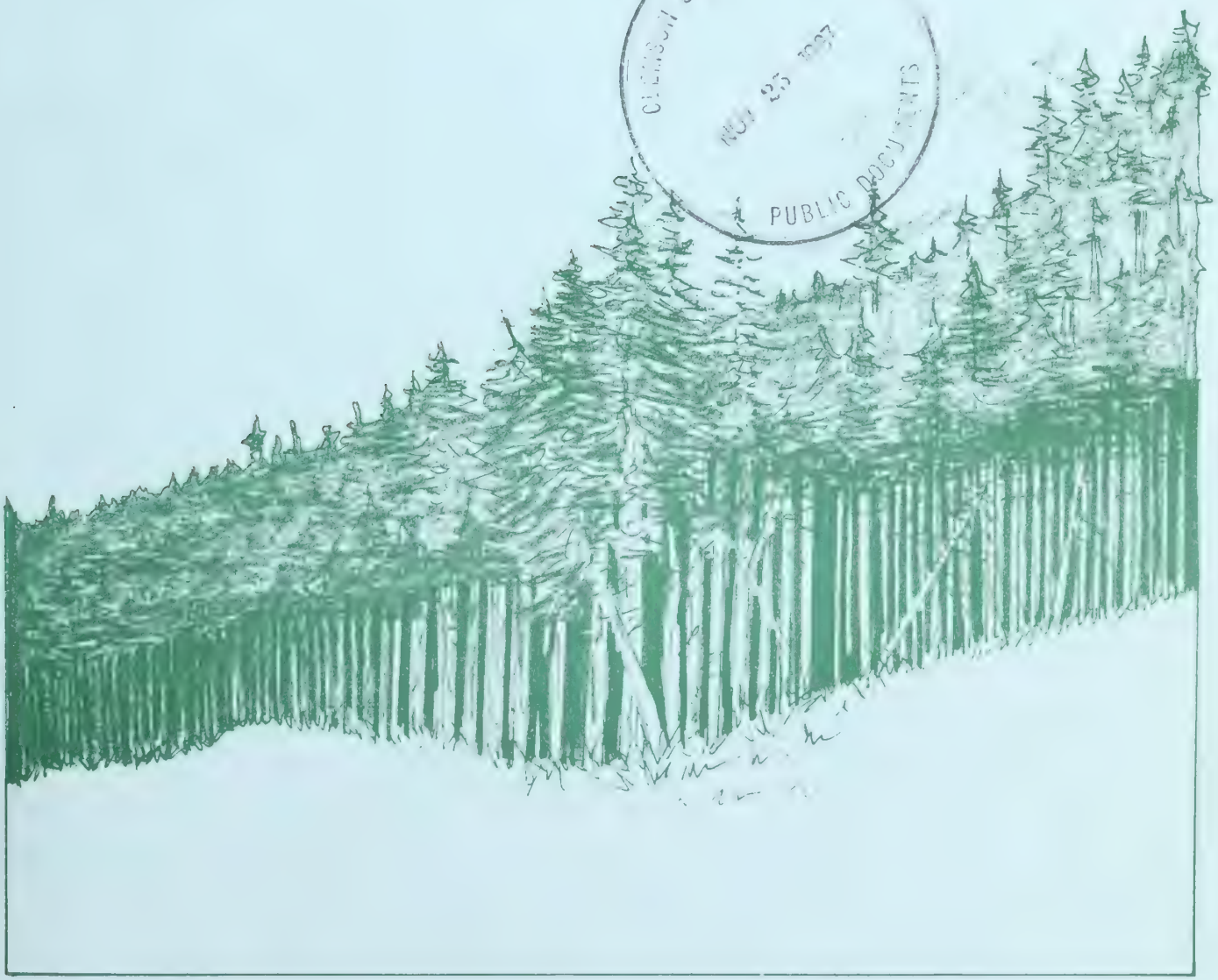
Pacific Northwest
Research Station

Research Paper
PNW-RP-384

Highly Stocked Coniferous Stands on the Olympic Peninsula: Chemical Composition and Implications for Harvest Strategy

Susan N. Little and Dale R. Waddell

CLEMSON UNIVERSITY
NOV 25 1987
PUBLIC DOCUMENTS



Authors

SUSAN N. LITTLE and DALE R. WADDELL are research foresters, Forestry Sciences Laboratory, P.O. Box 3890, Portland, Oregon 97208.

Abstract

Little, Susan N.; Waddell, Dale R. 1987. Highly stocked coniferous stands on the Olympic Peninsula: chemical composition and implications for harvest strategy. Res. Pap. PNW-RP-384. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 29 p.

This report presents an assessment of macronutrients and their distribution within highly stocked, stagnant stands of mixed conifers on the Quilcene Ranger District, Olympic National Forest, northwest Washington. These stands consisted of predominantly three species: western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), coast Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*), and western redcedar (*Thuja plicata* Donn ex D. Don). Preliminary investigation suggests that the living crown contains a small portion of the nutrient capital on the site. Extracting this material from the site during harvest or site preparation should not pose a threat to future production of biomass. Bioassays suggested that no macronutrients were deficient for growth of Douglas-fir seedlings. This study was one of several conducted on the Quilcene Ranger District for a better understanding of the economics, technology, and impacts of harvesting highly stocked, small-diameter timber.

Keywords: Whole-tree logging, nutrient budgets, site productivity, Washington (Olympic Peninsula), Olympic Peninsula—Washington.

Summary

In this paper, we investigate the amount and distribution of nitrogen, phosphorus, potassium, calcium, and magnesium within highly stocked, stagnant stands (doghair) of mixed conifers on the Quilcene Ranger District, Olympic National Forest, northwest Washington. These stands cor ,isted of predominantly three species: western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), coast Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*), and western redcedar (*Thuja plicata* Donn ex D. Don).

The amount of biomass in live trees at Quilcene is within the range of biomass values reported for other second-growth stands. Because of the vast quantity of dead material on the study sites, total aboveground biomass is comparable to that of old-growth stands. Likewise, nutrient capital for doghair stands compares favorably with that for other forest types. A large portion of the biomass and capital, however, is contained in dead material and in the forest floor.

Availability of soil nutrients was explored through bioassays of the surface soils. No macronutrients were found to be deficient for the juvenile growth of Douglas-fir.

Whole-tree harvesting should not adversely affect nutrient supplies on these sites. Care should be taken during harvest and site treatment, however, to protect the nutrient capital in dead material and in the forest floor.

Contents

1 **Introduction**

1 Nutrient Exports From Whole-Tree Harvesting

4 History of Doghair on the Quilcene Ranger District

4 Soils Underlying the Doghair Stands

4 **Objectives**

4 **Methods**

4 General Approach

4 Site Description

5 Chemical Composition of Stands

7 Deficiency Test: Bioassay Design

9 Statistical Analysis for Bioassay

9 **Results and Discussion**

14 **Conclusions**

17 **Acknowledgments**

17 **English Equivalents**

17 **References**

20 **Appendix 1**

20 Concentrations of Nutrients by Ecosystem Components

29 **Appendix 2**

29 Description of Soil Profile

Introduction

The Quilcene Ranger District, Olympic National Forest, has about 8000 ha of forest lands that are popularly known as doghair. These stands are stagnant and highly stocked—6,000 to 100,000 trees/ha—and have small average stem diameters. These stands comprise western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), coast Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*), and western redcedar (*Thuja plicata* Donn ex D. Don), ranging from 30 to 90 years old with average diameter at breast height (d.b.h.) less than 20 cm. Some of these stands are being whole-tree harvested; the intention is to convert to stands capable of producing saw timber. After harvest, some of these sites will be burned to reduce fire hazard and to expose mineral soil, which facilitates planting. The long-term impacts of these management options are not known. This study was designed to determine the distribution of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) in ecosystem components (crowns, boles, woody debris, forest floor, and soil) and any deficiency of these nutrients in the soil.

The study is part of a broader effort to investigate the technical and economic feasibility of harvesting doghair for fiber and fuel.[1/] Equations for predicting the biomass of trees and the average density of wood and bark in stems, essential for determining the nutrient content of trees, have been developed for these sites and are presented in previous reports (Pong and Waddell 1986).

Nutrient Exports From Whole-Tree Harvesting

Land managers have expressed concern that the removal of tree crowns during timber harvest may result in critical losses of nutrients and thereby reduce the future productivity of the site. The amount of nutrient capital contained in the crowns depends on species, age, site, and stand density. The relative contribution of crown material left on the site to future productivity depends on the amount of nutrients in the crowns, the amount and availability of nutrients in the forest floor and soil, and the rate of decomposition (Kimmins 1977). Estimates of the amount of N, P, and K in ecosystem components have been developed for some conifer forest types in the Pacific Northwest (Bigger and Cole 1983, Brown 1977, Grier and others 1974) (table 1, fig. 1). Morrison and Foster (1979) published estimates of N, P, K, Ca, and Mg for jack pine (*Pinus banksiana* Lamb.) stands in Ontario. Few studies, however, have been able to relate the amount of nutrients in tree boles and crown to the effects on productivity of removing that capital during harvest.

Some authors suggest that the effect of intensive harvests on site productivity is related to the age and productivity of the stand at the time of harvest (Cromack and others 1978, Kimmins 1977, Norton and Young 1976, Van Hook and others 1982). The age of the stand affects the amount and distribution of nutrients in the biomass. Switzer and others (1968) found that the amount of N in the foliage of *Pinus taeda* L. (loblolly pine) decreased in stands older than 15 years, whereas the amount of N in the stem and branch material continued to accumulate. They also discovered a decrease in the rate of storage (mean annual accumulation) for N, P, K, Ca, and Mg in the aboveground biomass with an increase in age.

[1/] Biomass estimation, production cost, and nutrient impacts of converting overstocked (doghair) stands to energy and fiber products. Interagency Agreement DE-AI79-84BP17609 between U.S. Department of Energy and USDA Forest Service. On file with Biomass Management and Utilization for Fiber and Energy Project, Portland, OR.

Table 1—Published biomass and nutrient budgets for coniferous forest types

Vegetation type, location, and source	Age	Component	Biomass	N	P	K	Ca	Mg
	Years		*Megagrams/ hectare*	*Kilograms / hectare*				
Douglas-fir: Pack Forest, WA (high site) (Bigger and Cole 1983)	53	Crown	37	250	40	101	—	—
		Bole	281	478	56	225	—	—
		Total tree above ground	318	728	96	326	—	—
		Forest floor	18	214	21	26	—	—
		Total above ground	336	942	117	352	—	—
		Soil to 50 cm	—	2066	—	—	—	—
Douglas-fir: Pack Forest, WA (low site) (Bigger and Cole 1983)	53	Crown	31	164	29	60	—	—
		Bole	134	161	27	81	—	—
		Total tree above ground	165	325	56	141	—	—
		Forest floor	14	187	19	27	—	—
		Total above ground	179	512	75	168	—	—
		Soil to 50 cm	—	483	—	—	—	—
Douglas-fir: H.J. Andrews Experimental Forest, OR (Grier and others 1974)	450	Crown	57	124	30	119	336	—
		Bole	473	189	12	123	284	—
		Total tree above ground	530	313	42	242	620	—
		Logs (residue)	55	132	9	20	80	—
		Litter (forest floor)	44	434	61	50	363	—
		Total above ground	629	879	112	312	1063	—
		Soil to 100 cm	—	4300	29	1	5500	—
Douglas-fir: Thompson Research Center, WA (Grier and others 1974)	37	Crown	31	163	41	100	179	—
		Bole	140	125	19	96	117	—
		Total tree above ground	171	288	60	196	296	—
		Logs (residue)	6	14	2	8	17	—
		Litter (forest floor)	16	161	24	24	120	—
		Total above ground	193	463	86	228	433	—
		Soil to 100 cm	—	2809	3871	234	741	—
Larch/fir: Ellensburg, WA (Brown 1977)	Uneven	Crown	72	288	67	258	427	46
		Bole	231	168	48	143	324	45
		Total tree above ground	303	456	115	401	751	91
		Dead (residue)	95	27	10	26	88	11
		Forest floor	32	308	31	25	354	423
		Total above ground	430	791	156	452	1193	325
		Soil to 60 cm	—	3314	25	657	3293	560
Larch/fir: Tonasket, WA (Brown 1977)	Uneven	Crown	30	141	26	138	218	16
		Bole	64	49	15	31	93	9
		Total tree above ground	94	190	41	169	311	25
		Dead (residue)	46	33	5	17	31	1
		Forest floor	29	327	29	30	457	17
		Total above ground	169	550	75	216	799	43
		Soil to 60 cm	—	6961	33	1716	12152	924
Jack pine: Ontario, Canada (Morrison and Foster 1979)	65	Crown	24	98	10	39	40	7
		Bole	90	82	4	50	87	12
		Total tree above ground	114	180	14	89	127	19
		Forest floor	26	283	13	680	396	157
		Total above ground	140	463	27	769	523	176
		Soil (A and B horizons)	—	2920	2152	80637	34406	21075

— not reported.

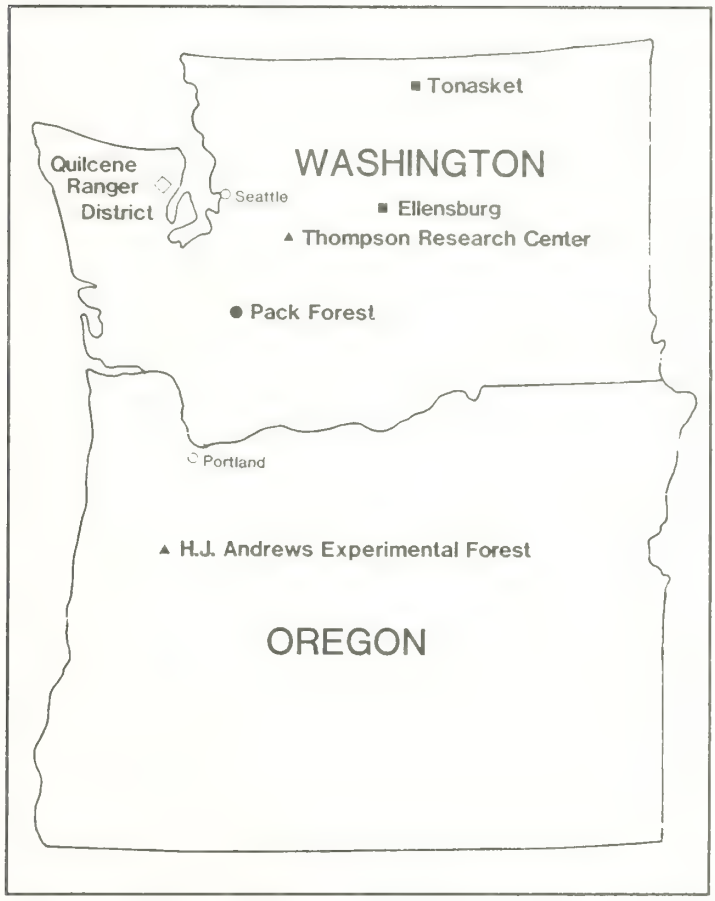


Figure 1—Location of Quilcene (◇) and study sites reported by Bigger and Cole (1983) ● Brown (1977) ■ and Grier and others (1974) ▲.

Work by Bigger and Cole (1983) suggests that crown material may hold a larger portion of aboveground nutrient capital on sites with lower productivity (table 1). On their Douglas-fir site with low productivity (low site), the crown component comprised 36 percent of the total N but only 16 percent on the site with high productivity (high site). This may indicate the importance of leaving crown material on poor sites to avoid depleting the existing nutrient capital. Two years after harvesting and planting, Bigger and Cole measured significantly less seedling growth on the sites (both high and low) that were whole-tree harvested than on the sites from which only boles were removed. Reduction in diameter growth was 4 percent on the high site and 21 percent on the low site, and the response in height growth was similar. Moisture and temperature extremes caused by lack of shade may have contributed to the reduction in growth on the sites that were whole-tree harvested.

History of Doghair on the Quilcene Ranger District

The current doghair stands were established after severe wildfires between 1891 and 1925 (Quilcene Ranger District, fire records). Most of the sites regenerated naturally. Planted sites are also overstocked. A large amount of woody debris is on these sites. Most of the western hemlock and Douglas-fir trees killed by fire have been incorporated into the forest floor; the larger western redcedar remain intact on the surface. Large amounts of unincorporated debris on the forest floor indicate that decomposition is slow, and nutrients bound in the forest floor are relatively unavailable to the current stand (Vitousek 1981).

Soils Underlying the Doghair Stands

The soils underlying these doghair stands are Entisols and Inceptisols that developed on deposits from continental glaciers (Soil Concept 22, Jennings and others 1982). These geologic materials vary in particle size and shape, the orientation of the strata, the degree of compaction, and their resistance to weathering. The soils are weakly developed (Birkeland 1977), lacking structure and differentiation of horizons; this has resulted in soils that are highly variable even within small areas of similar relief (Miller 1979). The soil is thought to be deficient in N and some micronutrients such as copper (Cu) and iron (Fe) and with perhaps toxic levels of manganese (Mn).[2/]

Objectives

The objectives of this study were twofold. The first objective was to estimate the amount of N, P, K, Ca, and Mg within components of the ecosystem: tree crowns, boles, and bark; dead trees and logs; forest floor and soil. Roots above mineral soil were considered to be part of the forest floor. Roots less than 2 mm within mineral soil were considered to be part of the soil resource. Large roots were not sampled. Levels of precision were not predetermined because sample size was limited by the cost of chemical analyses. The second objective was to determine which, if any, of those nutrients are deficient in the soil. Bioassays of individual sites with local Douglas-fir stock were used to test for deficiencies.

Methods

General Approach

Six sites on the Quilcene Ranger District were chosen for study and treated as one population for determination of biomass and nutrient capital. Two of the sites were designated harvest units on the Eightmile Creek drainage; the other four sites were delineated by stocking level on the Snow Creek drainage (fig. 2). Stand structure and biomass estimates were developed by Pong and Waddell (1986). Stocking levels for each site are summarized in table 2. A subsample of 33 live trees and 25 dead trees was selected from the biomass sample for nutrient analyses. Soil profiles were described at 25 locations over the six sites, and samples were taken at each location for nutrient analyses. Bioassays run on separate soil samples from four sites (Eightmile Creek 13, Eightmile Creek 19, Snow Creek 1, and Snow Creek 3) were used to test for nutrient deficiencies.

Site Description

The sites were inventoried with 60 circular 81-m^2 plots on a 61-m square grid. Data from these plots were used to build stand tables, which contain the number of trees within 2.5-cm-diameter classes for each of the three species. Dead trees of all species were combined into one category (the fourth "species") and sampled over the same diameter classes. Sample trees were randomly selected from the trees tallied on the 81-m^2 plots so that one live tree was selected for each species-diameter class. At least two dead trees were selected for each diameter class.

[2/] Wes Jennings, forest soil scientist, Olympic National Forest, Olympia, WA, personal communication, May 1984.

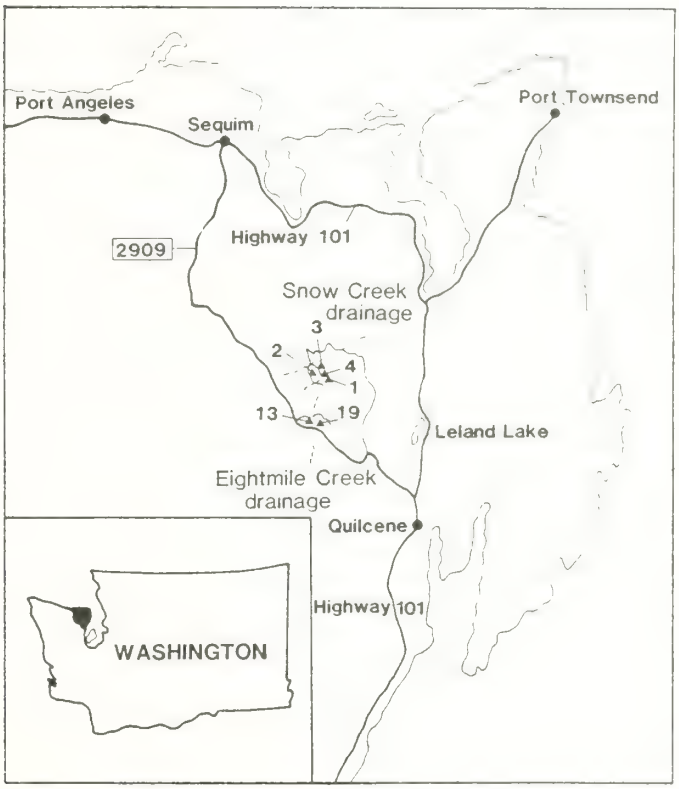


Figure 2—Location of study areas on the Quilcene Ranger District, Olympic National Forest.

Table 2—Stocking levels of study sites on the Quilcene Ranger District

Site	Live trees	Live and standing dead trees
	Trees / hectare	
Eightmile Creek 13	22,800	39,200
Eightmile Creek 19	6,400	8,400
Snow Creek 1	2,600	4,500
Snow Creek 2	5,300	8,000
Snow Creek 3	2,400	6,000
Snow Creek 4	5,300	10,200

Chemical Composition of Stands

All trees were sampled in August and September 1984. All biomass components were weighed in the field. Samples were taken at 1.5-m intervals along the bole for determination of moisture content. Figure 3 illustrates where samples were taken from a tree for determination of nutrient concentrations. Two disks were sampled from the bole—one at 1.39 m above the root collar and one at the base of the live crown. The disks then were separated into bark and wood, air dried, and analyzed. The crown was

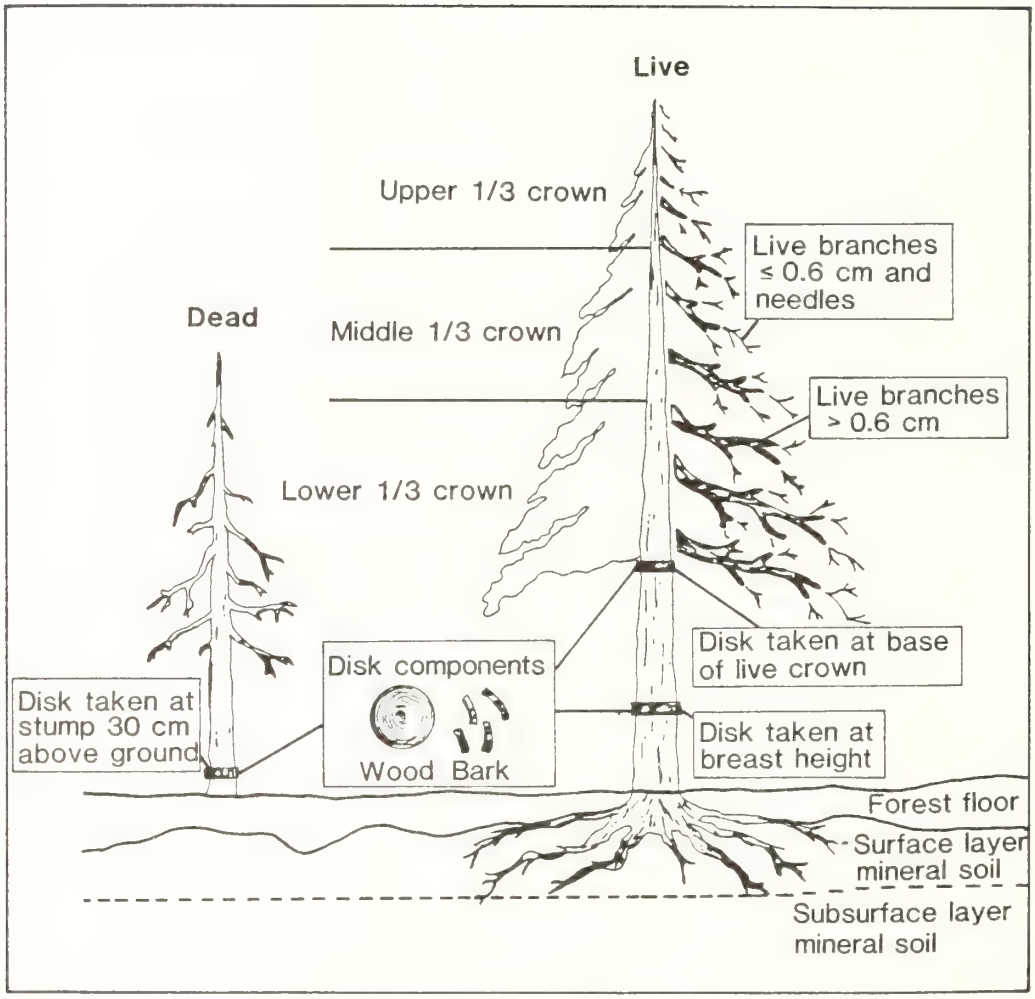


Figure 3—Components sampled from live and dead trees and soil for analyses of nutrient concentrations.

divided into six strata by size and vertical position in the tree: coarse (branches more than 0.6 cm in diameter) and fine (all materials less than 0.6 cm); lower, middle, and upper one-third of the crown. Trees less than 8 cm in d.b.h. had the same strata for size, but only two vertical strata—lower one-third and upper two-thirds of the crown. Each stratum was weighed, chipped, mixed, and sampled once for determination of moisture content and once for nutrient analyses.

Chemical analyses were conducted for N, P, K, Ca, and Mg by the Oregon State University Department of Forest Science. Samples for N and P analyses were digested by the micro-Kjeldahl method (350 °C; K_2SO_4, $CuSO_4$, and Se as catalysts) and analyzed with Scientific Instrument Continuous Flow Analyzer 200.[3/] Samples for

[3/] Mention of commercial names is for the information of the reader and does not constitute an official endorsement by the U.S. Department of Agriculture of any product or service to the exclusion of others that may be suitable.

cation (K, Ca, Mg) analyses were digested with perchloric acid and analyzed by Perkin-Elmer 4000 Atomic Absorption Spectrophotometer.

The concentration of each nutrient was multiplied by the dry weight of the component from which it was sampled. Nutrient weights were then summed for all components, resulting in a total capital for each tree. Total nutrient capital in aboveground biomass was estimated by applying these results to the stand tables generated from the inventory of the sites.

Residue biomass was estimated from line-intersect data taken on 240 15.24-m lines connecting the inventory plots (Brown 1974). Average nutrient concentrations determined for the dead trees were applied to the total biomass of residue per hectare for an estimate of nutrient capital in the residue.

A soil profile was described in each plot containing a sample tree. Bulk density was sampled at each plot in the surface and subsurface horizons by use of procedures outlined by Blake (1965). A sample was taken for determination of chemical concentrations from each of three layers: the forest floor, surface, and subsurface horizons (effective rooting depth). Nitrogen and phosphorus were determined by the same procedures used for plant materials; K, Ca, and Mg were determined by ammonium acetate extraction (Chapman 1965). Soil capital for each layer was calculated as the product of the concentration of nutrient, the bulk density, and the thickness of the layer. Soil capital was then averaged over all profiles for each nutrient.

Deficiency Test: Bioassay Design

The bioassay technique uses the biomass of plant material grown under controlled conditions to evaluate the availability of a given nutrient or set of nutrients. The technique assumes that, because other variables affecting the growth of the plant (such as water, light, and temperature) are controlled in the laboratory, differences in plant growth (weight of seedlings) between treatments can be attributed directly to the treatment (level of nutrient added or omitted).

Douglas-fir seedlings from seed collected on the Quilcene Ranger District[4] were used in the bioassay. Bioassays were completed for four sites: Eightmile Creek 13 and 19 and Snow Creek 1 and 3. Each bioassay consisted of 12 treatments (nutrient combinations) with five replicates per treatment (table 3). The quantity of fertilizer selected for each treatment was based on previous studies conducted on soils in the Pacific Northwest (Gessel and others 1979, Walsh and Beaton 1973).[5] Table 4 lists the form and dose of fertilizers used in the bioassays.

Each soil sample was dried, sieved to less than 1.3 cm with fines of organic matter included, and partitioned into 60 subsamples of equal weight. Dry fertilizers (KCl, $CaCO_3$, $MgCl_2$, S, and $CuCl_3$) were added directly to the soils. Each subsample was placed in a 3.8-liter plastic pot with saucer. NH_4NO_3 was added three times during the

[4] Seed stock number 926-82/205-09-221-02000-2.5-82-SIA, obtained from the USDA Forest Service Wind River Nursery, near Carson, WA.

[5] Donald Hauxwell, soil scientist, Humboldt State University, Arcata, CA, personal communication, May 1984; Richard E. Miller, principal soil scientist, Forestry Sciences Laboratory, Olympia, WA, personal communication, June 1984.

Table 3—Nutrients added for each treatment of the bioassay

Treatment[1/]	Nutrients added
All nutrients (N1)	N1, P, K, Ca, S, Mg, Cu
All nutrients (N1)	N2, P, K, Ca, S, Mg, Cu
–N	P, K, Ca, S, Mg, Cu
–P	N1, K, Ca, S, Mg, Cu
–K	N1, P, Ca, S, Mg, Cu
–Ca	N1, P, K, S, Mg, Cu
–S	N1, P, K, Ca, Mg, Cu
–Mg	N1, P, K, Ca, S, Cu
–Cu	N1, P, K, Ca, S, Mg
Control+N1	N1
Control+N2	N2
Control	None

[1/] "–" refers to nutrient excluded from treatment.

Table 4—Form and dose of nutrients used in bioassay treatments

Nutrient added	Form	Dose	
		Kilograms/ hectare	*Pounds/ acre*
N1	NH_4NO_3	184.0	200
N2	NH_4NO_3	368.0	400
P	P_2O_4	92.0	100
K	KCl	92.0	100
Ca	$CaCO_3$	92.0	100
Mg	$MgCl_2$	46.0	50
S	S	46.0	50
Cu	$CuCl_3$	4.6	5

experiment to avoid germination suppression. Phosphorus was added in aqueous solution after pots were thinned to three seedlings.

Each bioassay was configured in a completely random design. Thousand-watt halide lamps (phosphorus coated) were used with a photoperiod of 18 hours per day. Pots were no more than 2.5 m from the source. The soil surface in each pot was covered with an even layer of seed. The population in each pot was reduced to three plants after germination. Soils were kept moist with distilled water. Ambient temperature was kept at 10 °C by exhaust fans. After 6 months of growth, the seedlings in each pot were harvested, dried, and weighed to the nearest 0.1 g.

Statistical Analysis for Bioassay

An analysis of variance was conducted for each of the four soils. Multiple comparisons were made by use of Duncan's (1955) test. (Tukey's (1953) and Scheffe's (1950) tests provided similar results; only the values for Duncan's test are reported here.) A nutrient was considered deficient if the average weight of the bioassay for pots not receiving that nutrient was significantly less (at alpha = 0.05) than the average weight of pots with all nutrients added.

Results and Discussion

Table 5 summarizes biomass and nutrient capital for the average doghair site at Quilcene. Concentrations of nutrients within individual ecosystem components are discussed in appendix 1. Because standards for the amount of nutrients needed to grow trees on specific soil types have not been developed, we have no direct way of evaluating the amount of capital potentially lost during harvest from Quilcene doghair relative to site productivity. We also do not have nutrient capital estimates for similar stands on similar soils. Therefore, to evaluate our estimates for nutrient capital distribution in Quilcene doghair, we compare our results to nutrient capital estimates developed for other conifer types in the region (table 1, figures 4 through 10).

The amount of biomass in live trees at Quilcene is within the range of biomass values given for other second-growth stands. Individual trees are relatively small for their age. Total aboveground biomass at Quilcene is higher than that for Bigger and Cole's (1983) high site and is comparable to Grier and others' (1974) 450-year-old site. This may be due to differences in stand history. At Quilcene, the stands originated after wildfire that left large amounts of woody debris on the site. The second-growth stands at Pack Forest probably followed a commercial timber harvest and prescribed burn that left little woody debris. Even with these differences, the doghair at Quilcene is average in terms of total biomass production.

Likewise, quantities of nutrient capital for the stands compare favorably with those in other ecosystems. Total aboveground capital for the doghair is on a par with that for the old-growth stand reported by Grier and others (1974). The distribution of capital within the tree, however, seems more in line with the distributions found on the Bigger and Cole (1983) sites. Nutrient capital in the soil is well within the range of values given for other forest types. Hence, what is unique about doghair is not the amount of nutrient capital, but the distribution of that capital. A large portion of it is in dead trees and in the forest floor.

Table 5—Biomass and nutrient budgets averaged over all Quilcene sites

Component	Biomass	N	P	K	Ca	Mg
	Megagrams/ hectare	*Kilograms/hectare*				
Crown	27	135	42	90	164	28
Bole	217	159	41	156	322	49
Total tree above ground	244	294	83	246	486	77
Standing dead	15	14	3	4	27	3
Residue	100	93	20	27	180	20
Forest floor	244	1245	193	219	1234	359
Total above ground	603	1646	299	496	1927	459
Soil (effective rooting depth)	—	4534	3967	444	6691	928

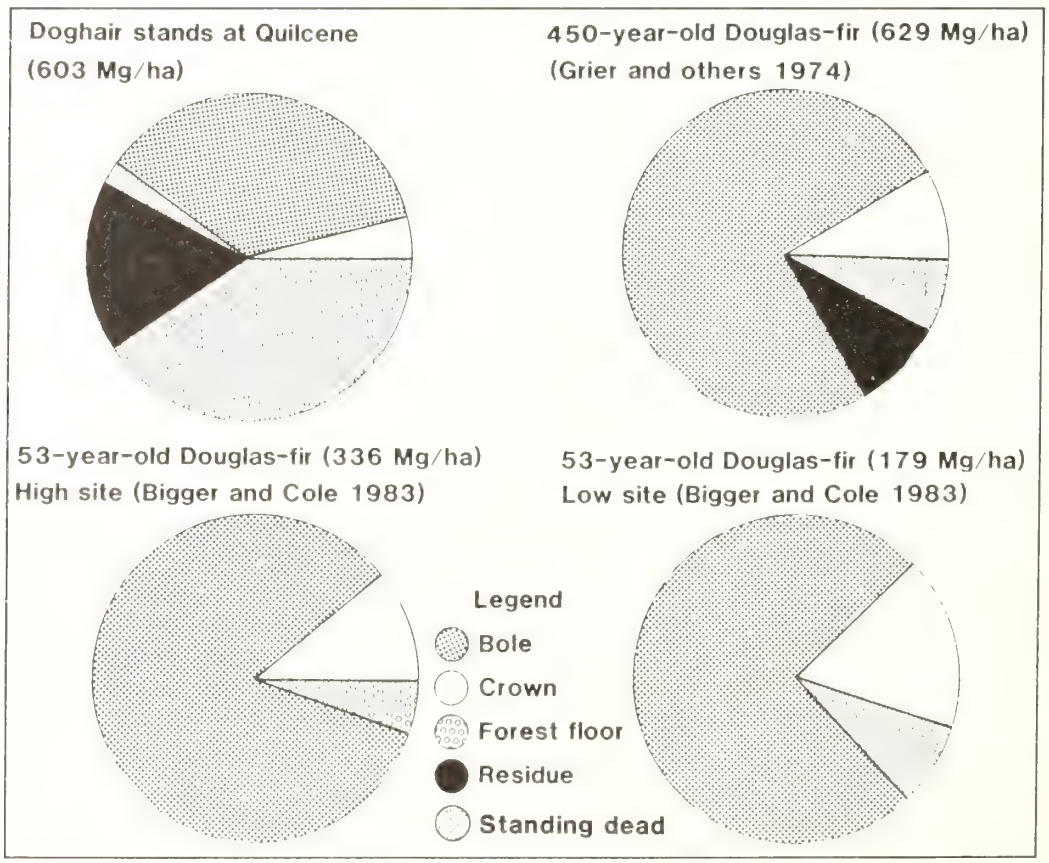


Figure 4—Comparison of biomass by components for Quilcene and published ecosystems.

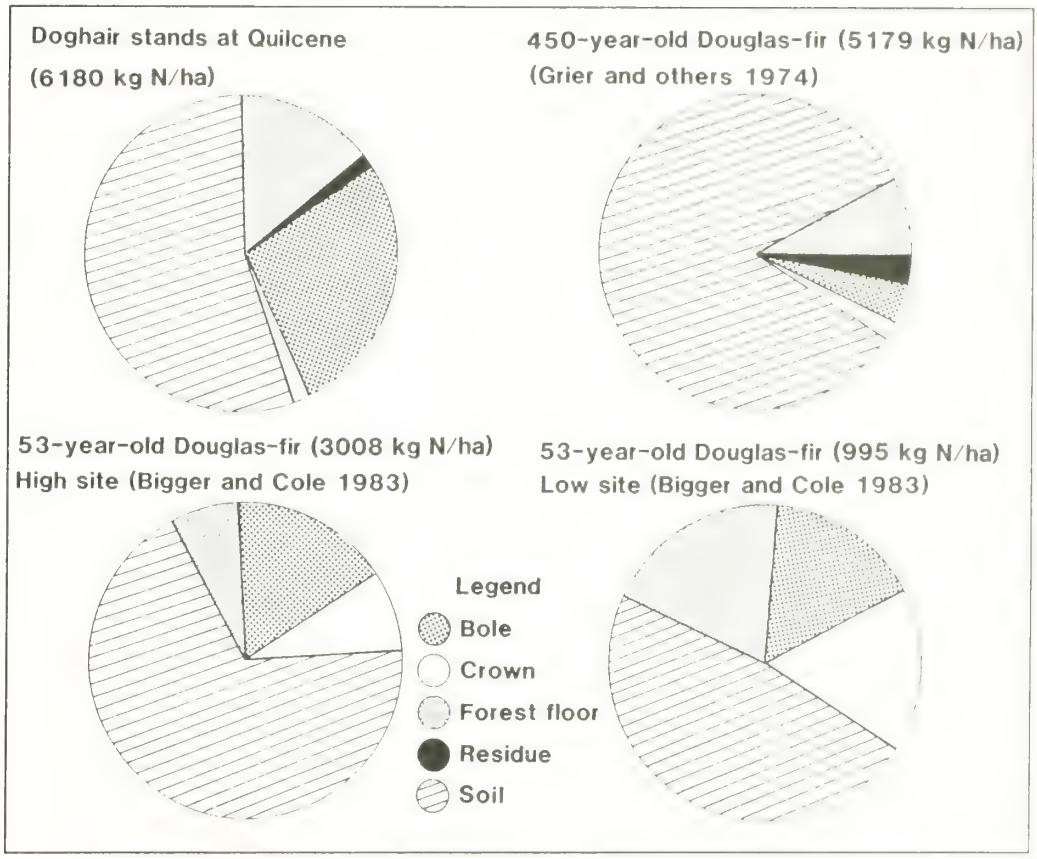


Figure 5—Comparison of nitrogen capital by components for Quilcene and published ecosystems.

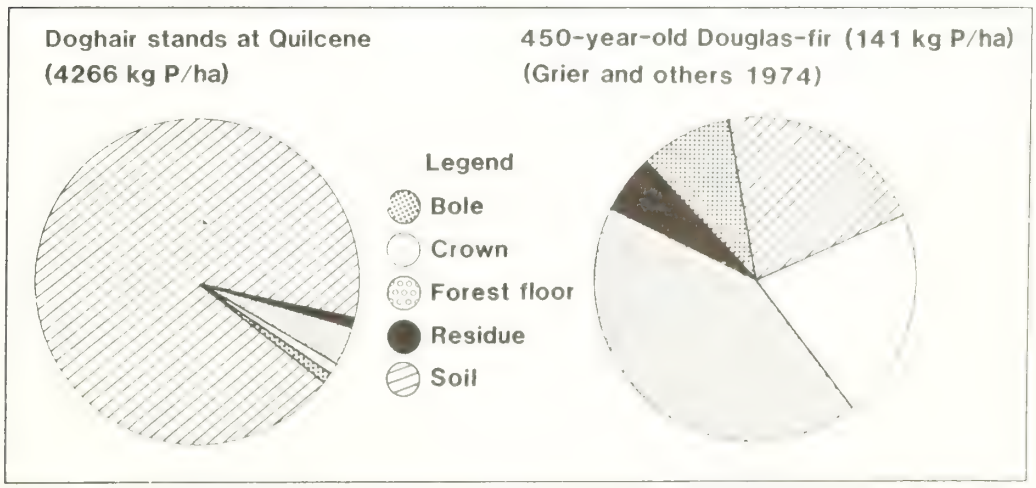


Figure 6—Comparison of phosphorus capital by components for Quilcene and a published ecosystem.

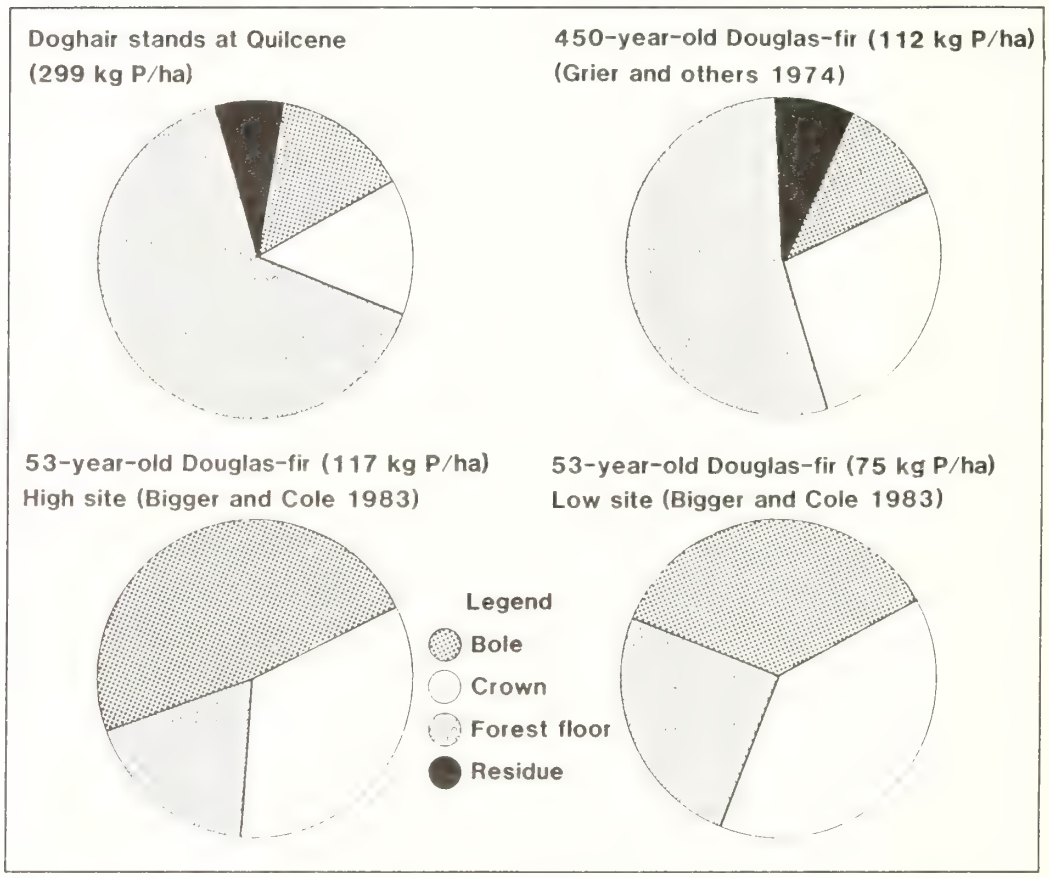


Figure 7—Comparison of phosphorus capital without soil by components for Quilcene and published ecosystems.

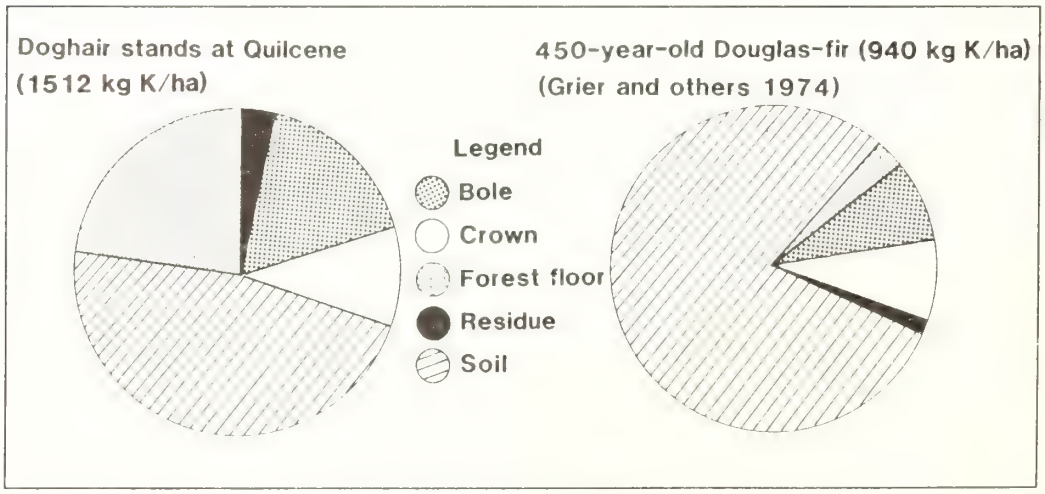


Figure 8—Comparison of potassium capital by components for Quilcene and a published ecosystem.

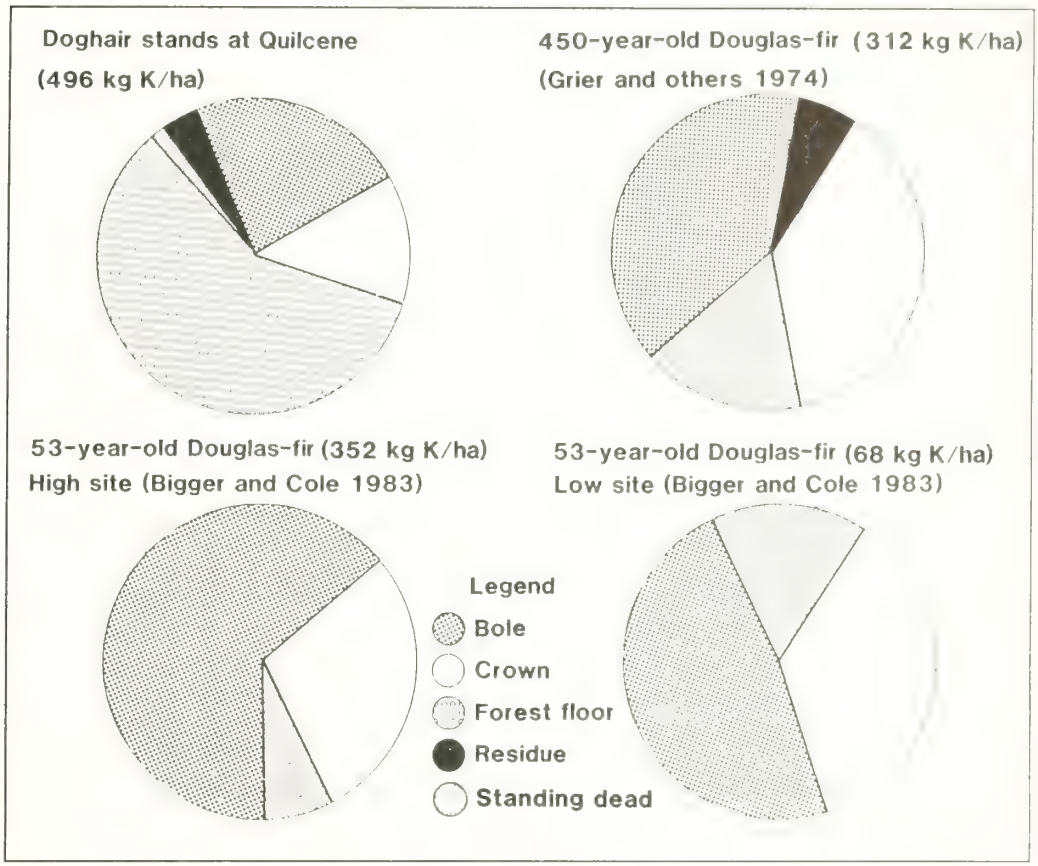


Figure 9—Comparison of potassium capital without soil by components for Quilcene and published ecosystems.

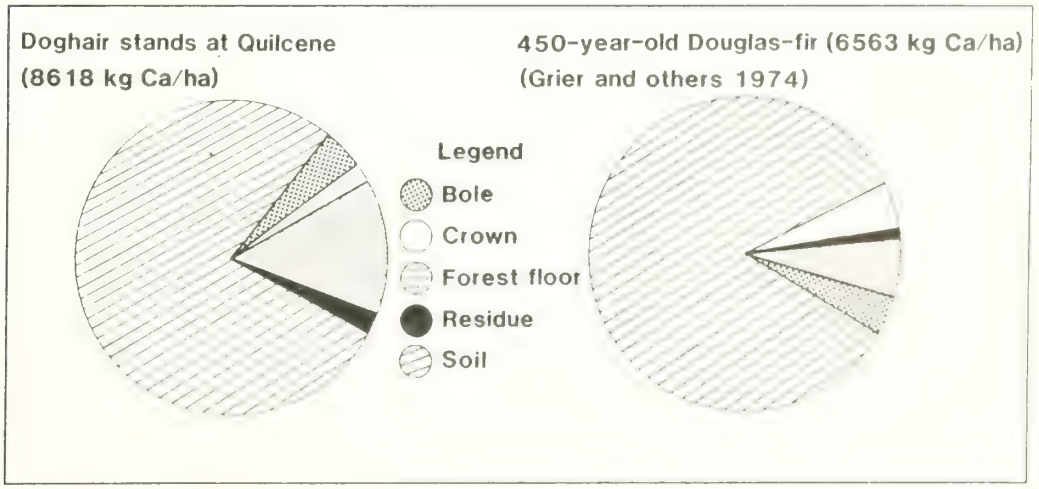


Figure 10—Comparison of calcium capital by components for Quilcene and a published ecosystem.

A description of a "typical" soil profile found on our study sites is presented in appendix 2. Generally, the soils are coarse in texture with large volumes of coarse fragments (greater than 35 percent by volume). Many of the subsurface layers are impermeable, as is evident by the shallow rooting depth (less than 50 cm).

Results of the bioassay are listed in table 6. Analysis of variance was significant (P less than or equal to 0.05) for all sites. Results of multiple comparisons of treatments are illustrated in figure 11. If no nutrients were deficient, we would expect to have no significant difference between treatments. If a treatment (dose of all nutrients except the one in question) had a significantly lower weight than the treatments that included all nutrients, we would conclude that that nutrient was deficient. We expected to see a deficiency in N and tested for two doses of N—184 kg/ha and 368 kg/ha. We therefore expected the –N treatment (all nutrients added except N) to be less than the controls with N added, and the all-nutrient treatments to have the largest weights. As figure 11 illustrates, we did not find the significant differences between treatments that would indicate a deficiency of N. The results showed no consistent deficiency for any of the other nutrients. The weights of the –Mg treatment are high for all soils. We suspect this response is due to a dose of Mg per treatment that was too high for the seedlings rather than a toxicity of Mg on site. Hence, in terms of macronutrient availability under controlled conditions, the soils at Quilcene do not appear to be deficient in nutrients.

Conclusions

In this study, we looked at an isolated portion of the doghair problem: nutrient capital and deficiencies of overstocked sites at Quilcene, Washington. We found that nutrient capital and availability were sufficient for tree growth on these sites. Productivity in terms of optimal product development seems to be primarily a problem of stocking control.

The results of this study provide insight into management implications of whole-tree harvesting of these stands. Because the nutrient capital in living crown materials constitutes a small portion of the total site capital, extracting this material from the site during harvest or site preparation activities should not pose a threat to biomass production in the near future. When harvest and site preparation methods are prescribed, consideration should be given to the amount of nutrient capital currently tied up in dead material and in the forest floor. Likewise, attention should be paid to the effects that management practices may have on the soil physical properties.

Future research should address strategies to regenerate these sites and investigate how harvest and site preparation methods affect stocking of the next stand. We have much to learn about the nutrient resources contained in the root systems of these stands and the role these reserves play in the productivity of the next rotation. The effects of intensive harvesting over several rotations on nutrient capital and productivity have yet to be explored for these sites.

Table 6—Average dry weights of bioassays by treatment[1/]

Treatment name	Eightmile Creek 13	Eightmile Creek 19	Snow Creek 1	Snow Creek 3
		Grams		
Control	0.58 (.26)	0.76 (.11)	0.96 (.21)	1.38 (.34)
Control+N1	1.62 (.37)	1.24 (.60)	1.20 (.37)	1.68 (.33)
Control+N2	1.22 (.48)	1.36 (.42)	.80 (.25)	1.36 (.51)
All-nutrients(N1)	1.82 (1.22)	1.70 (.60)	.92 (.55)	1.76 (.96)
All-nutrients(N2)	1.64 (.40)	1.86 (.78)	.42 (.16)	1.52 (.42)
–N	.94 (.23)	1.16 (.13)	.94 (.27)	.76 (.38)
–Ca	.82 (.24)	1.06 (.60)	.78 (.25)	1.08 (.65)
–Cu	1.32 (.31)	1.48 (.72)	.76 (.26)	1.72 (.62)
–K	1.78 (.54)	1.32 (.75)	.84 (.32)	1.18 (.70)
–Mg	1.88 (.44)	1.80 (1.09)	1.20 (.40)	1.84 (.68)
–P	1.16 (.53)	1.24 (.26)	.56 (.32)	1.34 (.47)
–S	.92 (.51)	1.35 (.19)	.56 (.09)	1.32 (.36)

[1/] Standard deviation is in parentheses. Sample size was 5 pots per treatment except –S for Eightmile Creek 19 (sample size 4); standard errors were within 6 percent of the mean for all sites.

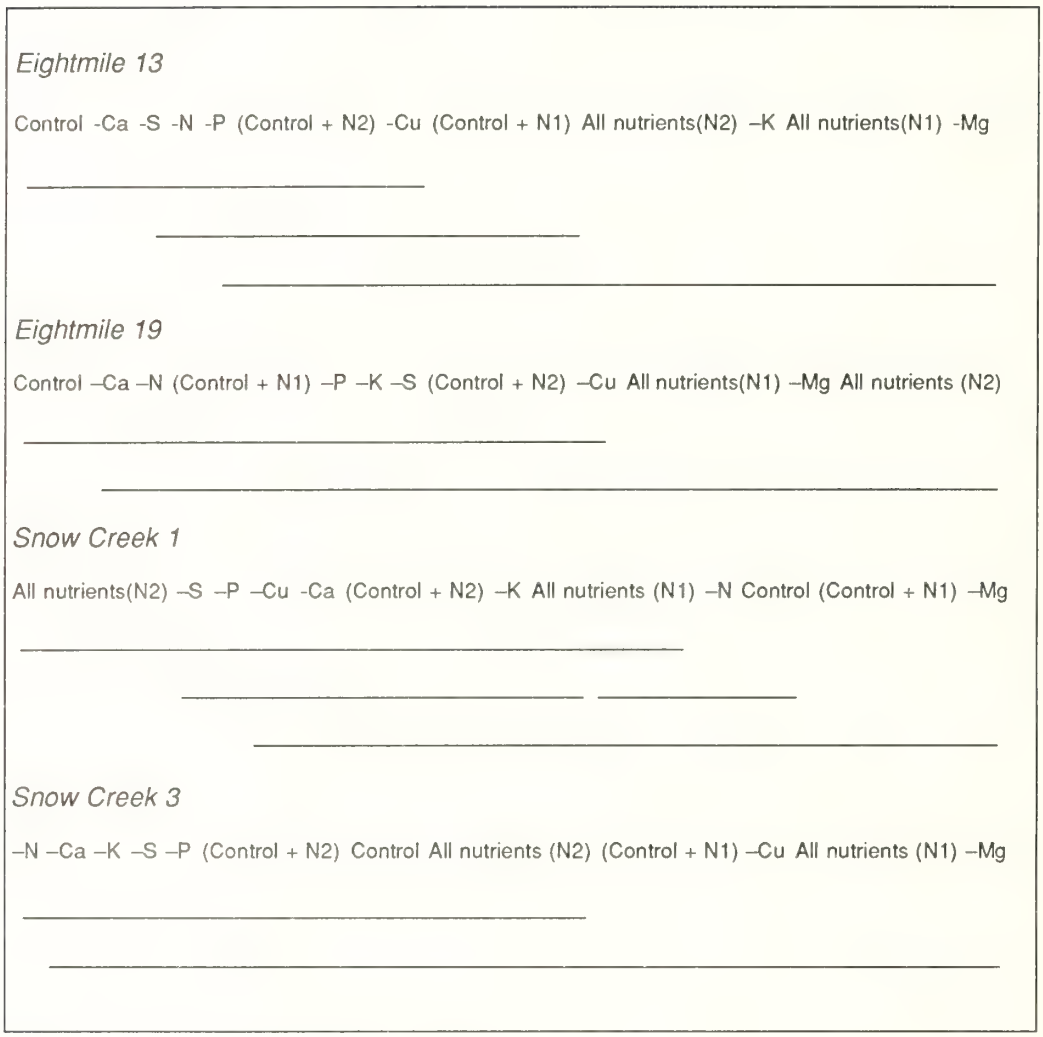

Eightmile 13
Control -Ca -S -N -P (Control + N2) -Cu (Control + N1) All nutrients(N2) –K All nutrients(N1) -Mg
Eightmile 19
Control –Ca –N (Control + N1) –P –K –S (Control + N2) –Cu All nutrients(N1) –Mg All nutrients (N2)
Snow Creek 1
All nutrients(N2) –S –P –Cu -Ca (Control + N2) –K All nutrients (N1) –N Control (Control + N1) –Mg
Snow Creek 3
–N –Ca –K –S –P (Control + N2) Control All nutrients (N2) (Control + N1) –Cu All nutrients (N1) –Mg

Figure 11—Duncan's multiple comparison of nutrient bioassays; treatments listed in order of increasing average dry weight; treatments over common bar are not significantly different at 95-percent level.

Acknowledgments

Funding for this study was contributed by the U.S. Department of Energy. The Quilcene Ranger Station of the Olympic National Forest provided additional support in laboratory space, study sites, and assistance in all aspects of fieldwork.

Special acknowledgment goes to Julianne K. Bulgrin for her support in the field and laboratory, assistance in data reduction, and illustration.

English Equivalents

When you know	*multiply by*	*to find*
millimeter (mm)	0.0394	inches
centimeters (cm)	0.3937	inches
meters (m)	3.2808	feet
hectares (ha)	2.4711	acres
grams (g)	0.0350	ounces
kilograms (kg)	2.2046	pounds
kilograms/hectare (kg/ha)	0.8926	pounds/acre
megagrams/hectare (Mg/ha)	0.4453	tons/acre
trees/hectare	0.4050	trees/acre
liter	1.057	quarts
degrees Celsius (°C)	1.8 and add 32	degrees Fahrenheit (°F)

References

Bigger, C. Mollie; Cole, Dale W. 1983. Effects of harvesting intensity on nutrient losses and future productivity in high and low productivity red alder and Douglas-fir stands. In: I.U.F.R.O. symposium on forest site and continuous productivity; 1982 August 22-28; Seattle, WA. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station:167-178.

Birkeland, Peter W. 1977. Pedology, weathering, and geomorphological research. New York, NY: Oxford University Press. 285 p.

Blake, G.R. 1965. Bulk density. In: Black, C.A., and others, eds. Methods of soil analysis, part 1. Agronomy 9: 374-390.

Brown, James K. 1974. Handbook for inventorying downed woody material. Gen. Tech. Rep. INT-16. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 24 p.

Brown, Terry Henry. 1977. Nutrient distributions of two eastern Washington forested sites. Pullman, WA: Washington State University. 111 p. Ph. D. thesis.

Chapman, H.D. 1965. Cation exchange capacity. In: Black, C.A., and others, eds. Methods of soil analysis, part 1. Agronomy. 9: 891-901.

Cromack, K., Jr.; Swanson, F.J.; Grier, C.C. 1978. A comparison of harvest methods and their impact on soils and environment in the Pacific Northwest. In: Youngberg, C.T., ed. Forest soils and land use, proceedings of the 5th North American forest soils conference; August 1978; Fort Collins, CO. Fort Collins, CO: Colorado State University, Department of Forestry and Wood Science: 449-476.

Duncan, D.B. 1955. Multiple range and multiple F tests. Biometrics. 11: 1-42.

Gessel, S.P.; Kenady, R.M.; Atkinson, W.A., eds. 1979. Forest fertilization conference; 1979 September 25-27; Union, WA. Inst. For. Resour. 40. Seattle, WA: University of Washington College of Forest Resources. 275 p.

Grier, C.C.; Cole, D.W.; Dyrness, C.T.; Fredriksen, R.L. 1974. Nutrient cycling in 37- and 450-year-old Douglas-fir ecosystems. In: Waring, R.H.; Edmonds, R.L., eds. Integrated research in the coniferous forest biome; CFB Bull. 5. Seattle, WA: University of Washington College of Forest Resources: 21-34.

Jennings, Wesley; May, Meredith; Sheehy, Gwen; Darling, Nancy. 1982. The Olympic National Forest soil resource inventory update report 1982. Olympia, WA: U.S. Department of Agriculture, Forest Service, Olympic National Forest. 158 p.

Kimmins, J.P. 1977. Evaluation of the consequences for future tree productivity of the loss of nutrients in whole tree harvesting. Forest Ecology and Management. 1: 169-183.

Miller, R.E. 1979. Response of Douglas-fir to foliar fertilization. In: Gessel, S.P.; Kenady, R.M.; Atkinson, W.A., eds. Forest fertilization conference; 1979 September 25-27; Union, WA. Inst. For. Resour. 40. Seattle, WA: University of Washington College of Forest Resources: 62-68.

Morrison, Ian K.; Foster, Neil W. 1979. Biomass and element removal by complete-tree harvesting of medium rotation forest stands. In: Impact of intensive harvesting on forest nutrient cycling; 1979 August 13-16; Syracuse, NY. Syracuse, NY: State University of New York, College of Environmental Science and Forestry: 111-129.

Norton, Stephen A.; Young, Harold E. 1976. Forest biomass utilization and nutrient budgets. In: Oslo biomass studies. Orono, ME. University of Maine Press: 55-73.

Ovington, J.D.; Madgwick, H.A.I. 1959. Distribution of organic matter and plant nutrients in a plantation of Scots pine. Forest Science. 5: 344-355.

Pong, W.Y.; Waddell, D.R. 1986. Harvesting overstocked stands of small diameter trees. Report 1: Stem density of western hemlock, Douglas-fir, and western redcedar; and Report 2: Biomass distributions of western hemlock, Douglas-fir, and western redcedar. Reports to the U.S. Department of Energy. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Scheffe, H. 1950. Statistical methods for evaluation of several constants and several sources of variability. Chemical Engineering Progress. 50: 200-205.

Switzer, G.L.; Nelson, L.E.; Smithe, W.H. 1968. The mineral cycle in forest stands. In: Forest fertilization—theory and practice. Muscle Shoals, AL: Tennessee Valley Authority: 1-9.

Tukey, J.W. 1953. The problem of multiple comparisons. Princeton, NJ: Princeton University.

U.S. Department of Agriculture. 1975. Soil taxonomy. Agric. Handb. 436. Washington DC: U.S. Department of Agriculture, Soil Conservation Service. 754 p.

Van Hook, R.I.; Johnson, D.W.; West, D.C.; Mann, L.K. 1982. Environmental effects of harvesting forests for energy. Forest Ecology and Management. 4: 79-94.

Vitousek, P.M. 1981. Clearcutting and the nitrogen cycle. In: Clark, F.E.; Rosswall, T., eds. Terrestrial nitrogen cycles. Ecological Bulletin (Stockholm). 33: 631-642.

Walsh, L.M.; Beaton, J.D. 1973. Soil testing and plant analysis. Madison, WI: Soil Science Society of America, Inc. 491 p.

Appendix 1
Concentrations of Nutrients by Ecosystem Components

Tables 7 through 10 list nutrient concentrations that have been averaged for all sample trees by component (crown, bole, bark) for each species. Concentrations were weighted by taking the average for all diameters of component nutrient capital divided by component weight. For crowns, the sum of individual stratum concentrations times the corresponding stratum weights was divided by the sum of stratum weights for each tree. The resulting concentrations were then averaged for all trees sampled by individual species.

Nutrient concentrations for individual components by diameter class are illustrated in figures 12 through 16. Concentrations did not vary with diameter for most components. Notable exceptions were concentrations in bark. Nitrogen and calcium increased with diameter; phosphorus decreased. Phosphorus tended to increase with diameter in small crown material.

Few data are published on nutrient concentrations relative to diameter at breast height for trees of similar age growing on the same soil. Ovington and Madgwick (1959) reported nutrient concentrations for 20 Scotch pine (*Pinus sylvestris* L.) trees in a 35-year-old plantation. They show a similar lack of trend for most nutrients and tree components. They did find a decrease in nitrogen concentration with increasing diameter for needles and live trees. They did not report concentrations for bark.

Table 7—Weighted average of nutrient concentrations by component for western hemlock, standard error (in parentheses), and sample size

Component	Unit	N	P	K	Ca	Mg
Crown material less than 0.6 cm in diameter	Percent	0.692	0.243	0.491	0.636	0.142
	Percent	(.221)	(.084)	(.222)	(.209)	(.050)
	Number of trees	12	12	12	12	12
Crown material greater than 0.6 cm in diameter	Percent	.149	.037	.013	.278	.038
	Percent	(.053)	(.013)	(.040)	(.106)	(.014)
	Number of trees	11	11	11	11	11
Bole wood	Percent	.054	.016	.050	.110	.018
	Percent	(.016)	(.005)	(.016)	(.033)	(.006)
	Number of trees	12	12	12	12	12
Bark	Percent	.204	.061	.325	.327	.050
	Percent	(.073)	(.019)	(.104)	(.123)	(.017)
	Number of trees	12	12	12	12	12

Table 8—Weighted average of nutrient concentrations by component for Douglas-fir, standard error (in parentheses), and sample size

Component	Unit	N	P	K	Ca	Mg
Crown material less than 0.6 cm in diameter	Percent	0.684	0.211	0.403	1.024	0.162
	Percent	(.198)	(.066)	(.125)	(.331)	(.050)
	Number of trees	12	12	12	12	12
Crown material greater than 0.6 cm in diameter	Percent	.211	.055	.146	.580	.059
	Percent	(.069)	(.019)	(.050)	(.184)	(.019)
	Number of trees	10	10	10	10	10
Bole wood	Percent	.050	.012	.041	.103	.017
	Percent	(.017)	(.004)	(.019)	(.034)	(.006)
	Number of trees	12	12	12	12	12
Bark	Percent	.206	.054	.187	.379	.045
	Percent	(.063)	(.016)	(.059)	(.146)	(.017)
	Number of trees	12	12	12	12	12

Table 9—Weighted average of nutrient concentrations by component for western redcedar, standard error (in parentheses), and sample size

Component	Unit	N	P	K	Ca	Mg
Crown material less than 0.6 cm in diameter	Percent	0.815	0.144	0.458	1.210	0.133
	Percent	(.234)	(.045)	(.157)	(.362)	(.042)
	Number of trees	9	9	9	9	9
Crown material greater than 0.6 cm in diameter	Percent	.167	.035	.147	.601	.041
	Percent	(.057)	(.012)	(.065)	(.195)	(.014)
	Number of trees	8	8	8	8	8
Bole wood	Percent	.066	.012	.045	.173	.020
	Percent	(.022)	(.004)	(.019)	(.060)	(.007)
	Number of trees	9	9	9	9	9
Bark	Percent	.245	.039	.275	.834	.063
	Percent	(.102)	(.016)	(.123)	(.381)	(.027)
	Number of trees	9	9	9	9	9

Table 10—Weighted average of nutrient concentrations by component for residue (dead trees and logs) and forest floor, standard error (in parentheses), and sample size

Component	Unit	N	P	K	Ca	Mg
Residue:						
Bole wood	Percent	0.049	0.010	0.012	0.098	0.014
	Percent	(.014)	(.004)	(.007)	(.033)	(.005)
	Number of trees	24	24	24	24	24
Bark	Percent	.309	.045	.088	.303	.045
	Percent	(.100)	(.013)	(.043)	(.110)	(.016)
	Number of trees	24	24	24	24	24
Forest floor	Percent	.510	.079	.090	.506	.147
	Percent	(.116)	(.016)	(.021)	(.123)	(.050)
	Number of trees	24	24	24	24	24

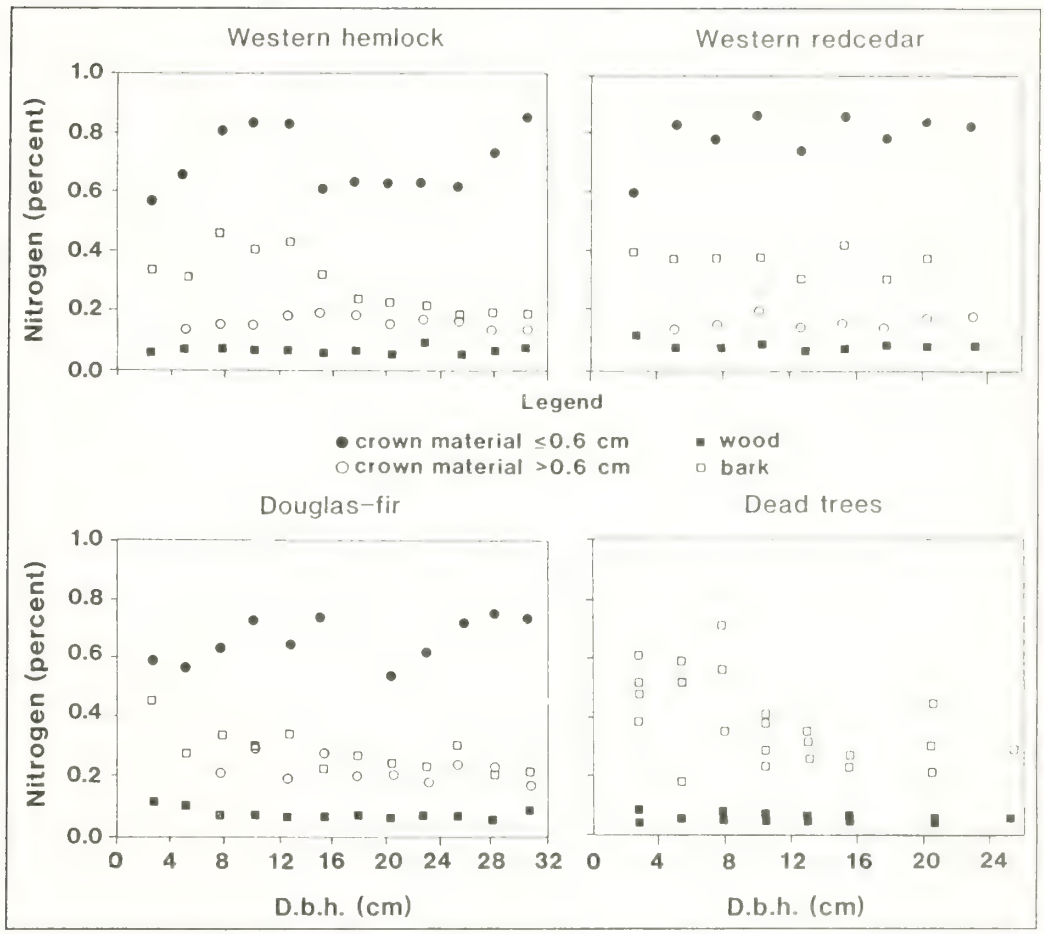


Figure 12—Concentrations of nitrogen by species and diameter.

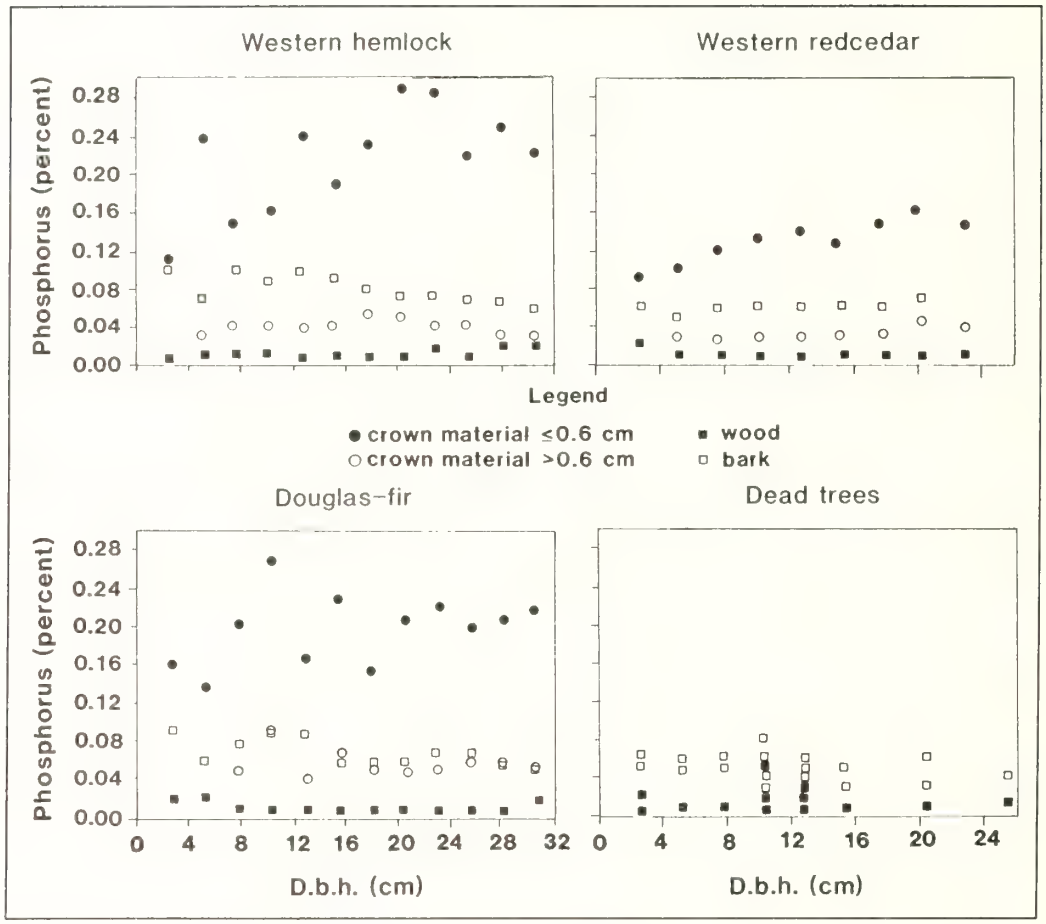


Figure 13—Concentrations of phosphorus by species and diameter.

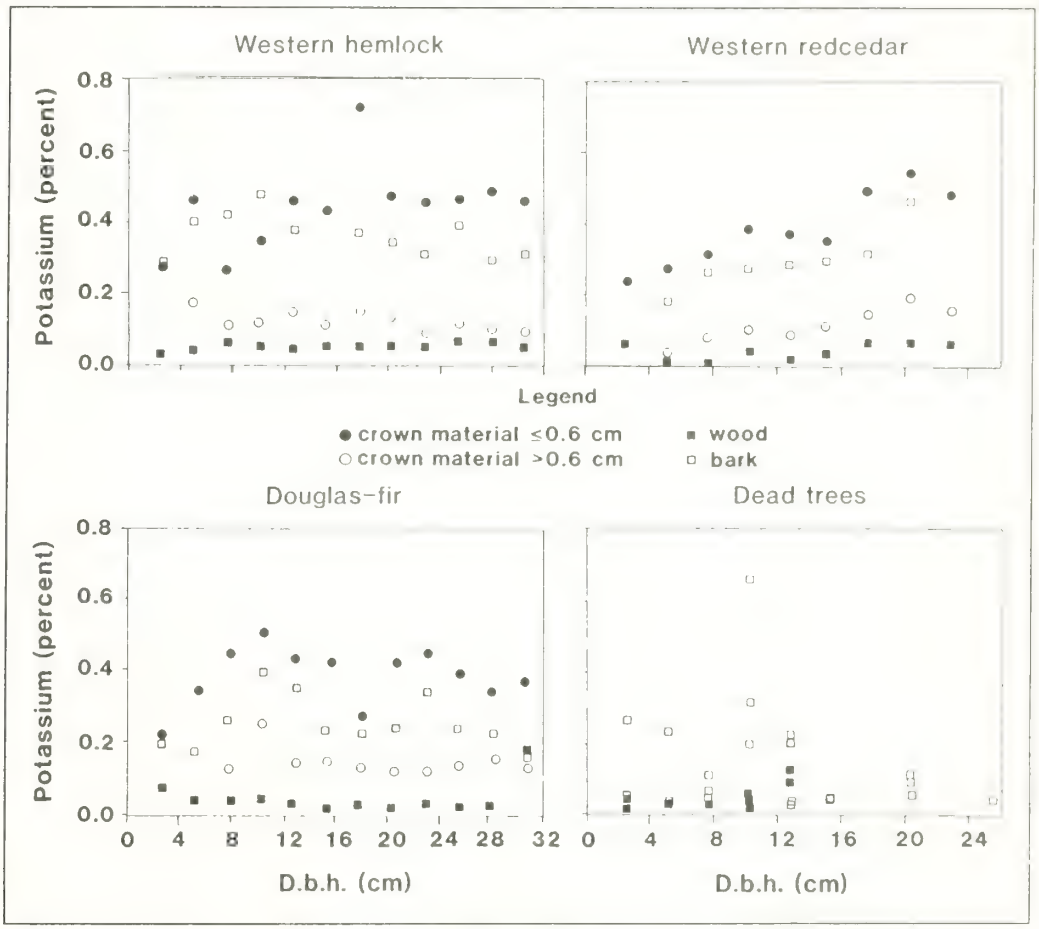


Figure 14—Concentrations of potassium by species and diameter.

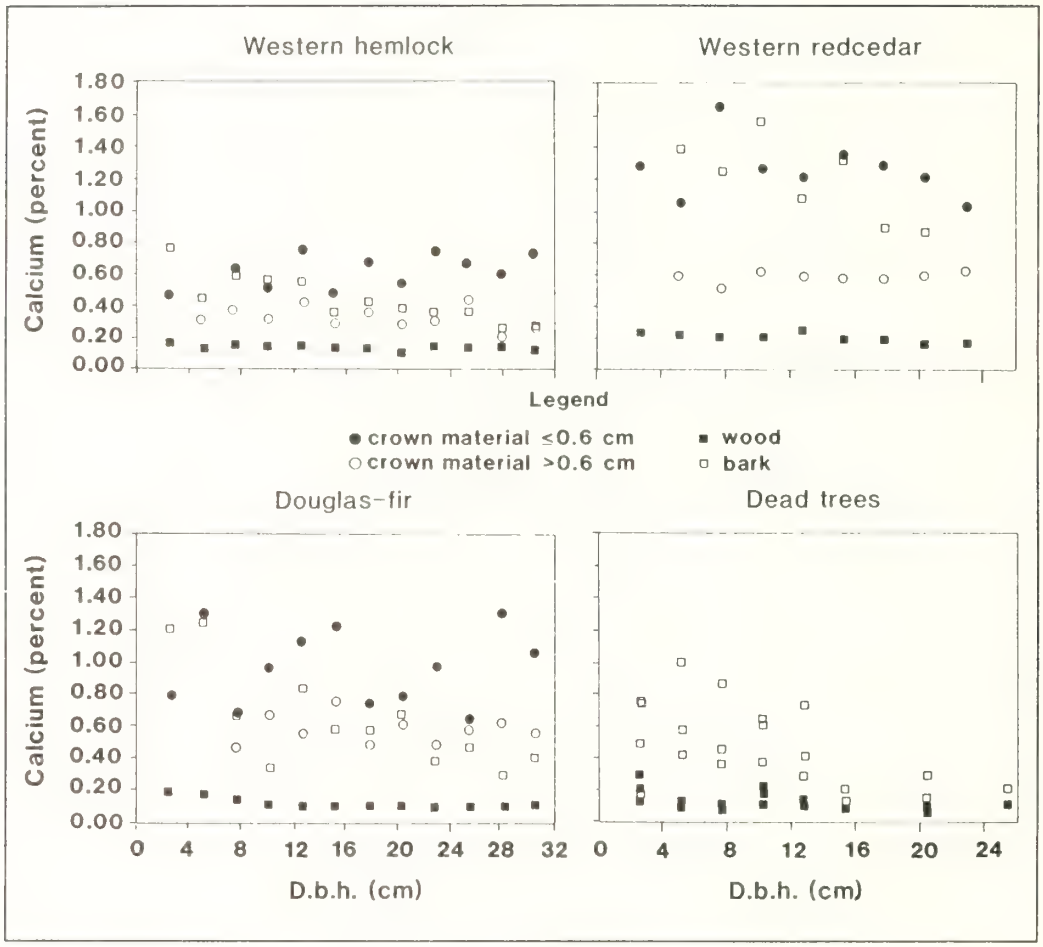


Figure 15—Concentrations of calcium by species and diameter.

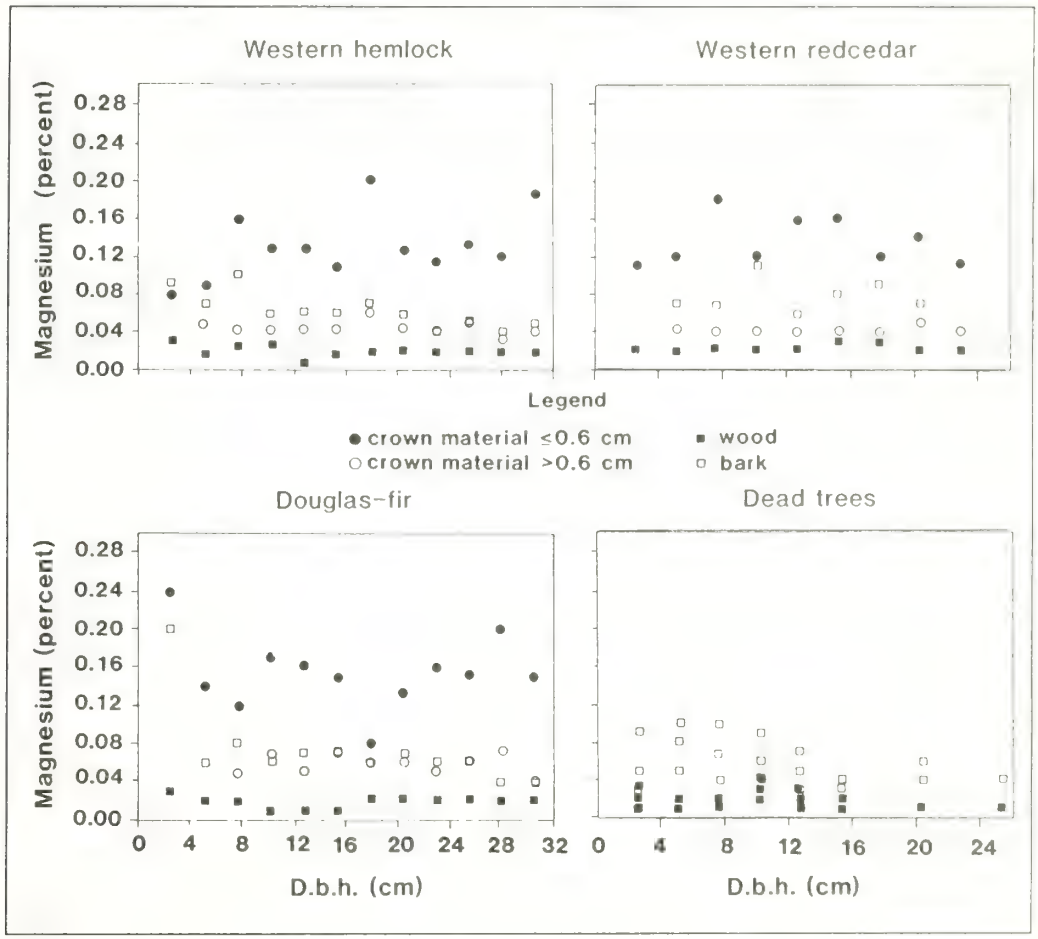


Figure 16—Concentrations of magnesium by species and diameter.

Appendix 2
Description of Soil Profile

Classification: See remarks.
Location: Clallam County, Washington. 11 km north of Quilcene, about 6.5 km west of Highway 101, on the Olympic National Forest. South of the 2814-2847 intersection on road 2847. Soil profile is located 76 m north of the road. SE1/4NE1/4 sec.18, R. 2 W., T. 28 N.

Physiographic position: Ridge side slope, 610-m elevation.
Topography: Undulating 15-percent slope.
Drainage: Moderately well drained.
Vegetation: Western hemlock, Douglas-fir, western redcedar.
Sampled by: Dale R. Waddell.
Remarks: Classification of profiles in this area is not consistent with concepts presented in U.S. Department of Agriculture (1975). Generally, the soils have characteristics of the Orthent suborder grading into the Ochrept suborder. Water movement in the surface horizon is rapid with significant slowing in the subsurface layers. Subsoils are compacted with evidence of some form of cementation.

01 15-3 cm. Conifer branches and needles.
02 3-0 cm. Partially decomposed conifer needles.

A 0-50 cm. Dark yellowish brown (10YR 4/4) gravelly sandy loam, yellowish brown (10YR 5/4) dry; fine granular to weak fine subangular blocky structure; loose (dry), very friable (moist), sticky, slightly plastic (wet); abundant roots in all sizes; clear wavy boundary; pH 5.4.

C 50-254 cm. Dark yellowish brown (10YR 4/4) gravelly sandy loam with light brown gray (10YR 6/2); few fine mottles, light yellowish brown (10YR 5/6) dry; massive; soft (dry), friable (moist), sticky, slightly plastic (wet); few medium roots; gradual irregular boundary; pH 6.0.

Little, Susan N.; Waddell, Dale R. 1987. Highly stocked coniferous stands on the Olympic Peninsula: chemical composition and implications for harvest strategy. Res. Pap. PNW-RP-384. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 29 p.

This report presents an assessment of macronutrients and their distribution within highly stocked, stagnant stands of mixed conifers on the Quilcene Ranger District, Olympic National Forest, northwest Washington. These stands consisted of predominantly three species: western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), coast Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*), and western redcedar (*Thuja plicata* Donn ex D. Don). Preliminary investigation suggests that the living crown contains a small portion of the nutrient capital on the site. Extracting this material from the site during harvest or site preparation should not pose a threat to future production of biomass. Bioassays suggested that no macronutrients were deficient for growth of Douglas-fir seedlings. This study was one of several conducted on the Quilcene Ranger District for a better understanding of the economics, technology, and impacts of harvesting highly stocked, small-diameter timber.

Keywords: Whole-tree logging, nutrient budgets, site productivity, Washington (Olympic Peninsula), Olympic Peninsula—Washington.

The **Forest Service** of the U. S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives—as directed by Congress—to provide increasingly greater service to a growing nation.

The U.S. Department of Agriculture is an Equal Opportunity Employer. Applicants for all Department programs will be given equal consideration without regard to race, color, sex, religion, or national origin.

Pacific Northwest Research Station
319 S.W. Pine St.
P. O. Box 3890
Portland, Oregon 97208

October 1987

U.S. Department of Agriculture
Pacific Northwest Research Station
319 S.W. Pine Street
P.O. Box 3890
Portland, Oregon 97208

Official Business
Penalty for Private Use, $300

BULK RATE
POSTAGE +
FEES PAID
USDA-FS
PERMIT No. G-4

do NOT detach label

United States
Department of
Agriculture

Forest Service

Pacific Northwest
Research Station

Research Paper
PNW-RP-385

SPATS: A Model for Projecting Softwood Timber Inventories in the Southern United States

David J. Brooks

Author

DAVID J. BROOKS is a research forester, Forestry Sciences Laboratory, P.O. Box 3890, Portland, Oregon 97208.

Abstract

Brooks, David J. 1987. SPATS: a model for projecting softwood timber inventories in the Southern United States. Res. Pap. PNW-RP-385. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 23 p.

The yield-table projection method for modeling the development of regional timber inventories is outlined, and its application to softwood timber types in the Southern United States is described. Problems of simulating forest management practices and natural succession are discussed. A computer model that projects softwood timber inventories using yield-table projection and stand regeneration using a Markovian probability structure is presented. The methodology and projections of this model are compared with alternative approaches to predicting future timber inventories in this region.

Keywords: Yield-table projection, inventory models, softwood timber supply, South.

Research Summary

Simulating the development of regional forests is an essential component of long-term timber supply studies. The Southern Pine Age-class Timber Simulator (SPATS) was designed to be used in conjunction with a model of North American timber markets. The SPATS model can also be used as a "stand-alone" simulator of softwood forests in the Southern United States.

Yield-table projection is an approach to timber inventory modeling in which forest area and yield are represented by stand age and other characteristics. Among the forest characteristics identified are management regimes that include stand origin and harvest age. Yield-table projection is essentially an elaborate bookkeeping framework in which biological and human processes are simulated with sets of rules for removing, shifting, and replacing area cells in the initial distribution. These rules are summarized as sets of equations.

Two types of model validation are discussed. In one, the model structure is examined to ensure that the pieces are complete and correctly assembled. In a second type of validation, model output is examined and, if possible, compared with actual results. In long-term projection models, only the first type of validation is possible.

Comparing projections made by different models, with similar input data, is useful, however. Therefore, the SPATS model is compared to another timber resource inventory model. Projections made by use of these models are similar. Although this comparison cannot be considered a validation of either model, it does provide useful insights. One important result is the implication that projection models can be operated with a greater degree of data aggregation when critical model routines rely on simple proportionality assumptions.

Information on operating SPATS, a description of the stationary Markov regeneration model, a table of model variable definitions, and sample data files are included as appendixes.

Contents

1 **Introduction**

1 **Background**

3 **Yield-Table Projection**

4 **The Southern Pine Age-Class Timber Simulator**

7 **Model Validation**

13 **Literature Cited**

14 **Appendix 1**

14 Operation Notes

17 **Appendix 2**

17 The Stationary Markov Regeneration Model

19 **Appendix 3**

19 Description of Variables

20 **Appendix 4**

20 Annotated Data Files

Introduction

Modeling the development of regional forests is a macroanalytical complement of modeling individual stand or forest growth and yield. Macroanalysis of forest resource development emphasizes aggregate measures of resource conditions, such as total timber growing stock, the balance of net growth and drain, and broad categories of forest management. The outlook of regional projection models is commonly long term (50 or more years).

Two methods are commonly used to model timber inventories of large regions; these are stand-table projection and yield-table projection. Stand-table projection uses a frequency distribution of the number of trees (per unit area) arrayed by diameter class. Projections are produced by adjusting this distribution based on diameter growth and tree mortality (including harvest). Yield-table projection, used in the model reported here, uses a classification of the regional forest according to age groups and additional stand characteristics. A third projection method, based on the simulation of individual tree growth, has had limited application in long-term projection for large areas. Alig and others (1984) review timber inventory projection methodologies and specific models in some detail.

Computer models that simulate forest resource development can be further classified as either descriptive or optimizing. For descriptive models, output is interpreted as a conditional projection of future conditions, given that critical variables are at their assumed values over the projection period. The input data and assumptions of the model are intended to reflect "most likely" behavior under different sets of assumptions. In contrast, optimizing models are characterized by the use of an objective function that is either maximized or minimized, thereby yielding values of the critical decision variables. Optimizing models project resource development conditioned on behavior following a computed optimal path. Descriptive models use explicit assumptions about the values of these decision variables to generate the predicted values of the model system.

This report documents a computer model that was developed to provide descriptive projections of future softwood timber inventories in the Southern United States. The Southern Pine Age-class Timber Simulator, SPATS, was designed to support an analysis of public policy targeting nonindustrial private owners (Brooks 1985). This policy analysis linked SPATS with TAMM, the Timber Assessment Market Model (Adams and Haynes 1980), a market- simulating, spatial equilibrium model of North American softwood timber and product markets. A model of economic behavior in timber markets (such as TAMM) and a model of timber inventory development together provide an opportunity to examine the interaction of the supply and demand for timber in both the long term and the short term.

Background

At the time SPATS was developed (1981), the computer model used by the USDA Forest Service to make long-term timber inventory projections was the Timber Resource Analysis System (TRAS) (Larson and Goforth 1974). Simulations of the development of North American timber markets using the Timber Assessment Market Model, in which TRAS is incorporated, are described by Adams and Haynes (1980).

The TRAS model has two major shortcomings when it is used for long-term projections of inventory development. First, incorporating into TRAS data sets assumptions about future forest management activity is difficult, and it is both more important and more difficult when future management is assumed to be significantly different from historical management. Adams and others (1982) describe simulations, using TRAS, of intensive forest management that required considerable artistry and program modification.

The second shortcoming is the implicit assumption in TRAS that the stand-type composition of modeled forests will remain unchanged. This assumption fails to take into account changes resulting from increased forest management (plantation establishment, for example), or changes that are the result of natural succession toward climax forest types. With these limitations, TRAS was not suitable for use in the study for which SPATS was developed, and doubts were raised about the reliability of TRAS-based projections of timber inventories for the South.[1]

Brooks (1985) used SPATS to develop a view of the future of southern forests in contrast to that provided by TRAS projections, and to examine the impact of alternative policy and planting strategies on this future. Since that study was completed, some developments require a revision to the presentation of the SPATS model but do not eliminate its relevance or its usefulness.

First, and most important, was the development of the Timber Resource Inventory Model (TRIM) (Tedder and others 1987). Like SPATS, TRIM is a yield-table projection model; however, TRIM has much more in common with the Timber Resource Economic Evaluation System (TREES) (Tedder and others 1980). The TRIM model was designed to represent forests of either large or small areas in any region of the United States, using forest survey plot data with flexible (user-determined) aggregation schemes. The SPATS model was designed to model only the private forests of the Southern United States, and although the data for SPATS are also derived from forest survey plot data, they are aggregated outside the model. The objectives underlying the development of SPATS were more focused and modest.

A second event, taking place at the same time that TRIM was being developed, was the undertaking of a comprehensive review of the present and the likely future conditions of southern forests. Because the TRAS-based projections had potentially serious biases, a review committee that collected additional data was formed. This committee conducted a broad review of assumptions about the future management of forests in the South and the demand for forest products (USDA Forest Service 1987); the TRIM model was used to develop resource projections for this study.

The relevance of these developments to SPATS, and to this document, is that a comparison of SPATS to TRAS is no longer necessary, nor particularly meaningful,

[1] For example, compare projections in USDA Forest Service (1982) and the discussion in Boyce and Knight (1979).

in spite of the fact that TRAS-based projections dominate the literature (USDA Forest Service 1982). Five years ago it was necessary to make a case for an alternative view of the future of southern forests, based on the projections of a yield-table model; however, the usefulness of a yield-table model for projecting the development of the softwood forests of the Southern United States is now generally accepted. Therefore, analysts and policymakers must consider questions about the appropriate features of yield-table models. In this context, a comparison between SPATS and TRIM may be useful.

The remainder of this report contains a description of the yield- table projection methodology, an outline of the algorithm used in SPATS, and a discussion of model validation in which projections using SPATS and TRIM are compared. Further documentation of the SPATS computer program is in the appendixes.

Yield-Table Projection

Yield-table projection is a relatively simple, but versatile, approach to timber inventory projection. The forest is represented by a matrix that describes the distribution of forest area by age class and additional stand descriptors. These descriptors may include stand type, site class, stocking level, and management regime. Noncontiguous areas with identical descriptors are grouped for projection purposes.

Timber yields (per unit area) must be specified with the same descriptors as the area data. The product of the area matrix and yield matrix, summed over all age and type classes, is the total timber volume of the forest. In a yield-table model, the process of inventory projection is reduced to a bookkeeping problem: keeping track of the distribution of acres as they advance through age classes, are harvested, and (perhaps) change type descriptors, through time.

Forest management activity can be simulated in the yield-table framework by using the type descriptor to identify stands subject to different management regimes, as well as stands with different species composition. These regimes can include stand origin, intermediate treatments, and final harvest age. In yield-table projection models, harvesting is typically assumed to be based on even-aged management, although a more diverse approach to stand management can be represented. The assumption of even-aged management is embedded in the use of a single age class (usually the oldest available) for final harvesting. The representation of partial cutting in stands of a wide range of ages is especially difficult to represent in highly aggregated yield-table models.

The amount of model detail that is required to adequately represent the forest of a region is a function of the biological characteristics of the forest, the nature of management activity, and the purposes for which the projection is done. In principle, the representation of any set of management practices can be accomplished by expanding the type dimension of the yield-table model, with each type category representing a different management regime; however, there are practical problems that discourage unlimited expansion of this kind. As the basic dimensions of the model are expanded, there must be a concomitant expansion of associated data and model routines.

In the absence of data, assumptions must be made. In practice, model detail is often achieved, or at least supported, by means of broad assumptions or simple assertions.

The amount of detail in a regional inventory model should also be consistent with the relative importance of the details to model projections. In this context, the use to which the inventory model projections will be put must be kept in mind. When SPATS was developed, for example, this was a matter of identifying the features of southern forests that are most subject to change, and for which changes will alter projections of long-term timber supplies. Long-term market projections made with TAMM use annual estimates of total regional growing stock (by owner) to shift short-term, private, timber supply functions. Therefore the magnitude of the potential effect on growing stock was used as a measure of the importance of particular model features.

The Southern Pine Age-Class Timber Simulator

The basic bookkeeping algorithm of the SPATS model can be summarized in general terms as:

$$A_{j,k,t+1} = A_{j-1,\,kt} - H_{j-1,kt}\text{, for } 2 < j < J; \tag{1}$$

$$A_{J,k,t+1} = (A_{Jkt} - H_{Jkt}) + (A_{J-1,kt} - H_{J-1,kt})\text{; and} \tag{2}$$

$$H_{jkt} = R_{jkt} / y_{jkt}\ ; \tag{3}$$

where, subscript t indicates the period (the age class interval is 5 years); j is the age class (J indicates the oldest age class), and k is the stand type descriptor; A_{jkt} is the area in stands of type k, age class j at time t; H_{jkt} is the area of these stands harvested in time t; R_{jkt} is the volume harvested; and y_{jkt} is the yield per unit area. Twenty 5-year age classes are used in SPATS (the 0 age class indicates nonstocked acres); four stand types are modeled: natural pine, plantation pine, oak-pine, and hardwood.

Equations (1–2) advance the forest through age classes after accounting for harvest in the current period. In equation (1), the area in an age class in any period is defined as the area in the next youngest age class in the previous period, less the area harvested from the younger age class. Equation (2) treats the special case of the oldest age class, J. This age class contains any stands of this age class uncut in the previous period (the first expression), plus the uncut stands that were in age class J-1 in the previous period. The oldest age class is defined as an accumulating class; that is, it represents the area in stands at or older than a nominal maximum age.

Total harvest volume is determined exogenously and is converted to area (by age class) in equation (3). The distribution of harvest volume across type and age classes (R_{jkt}) is determined by simple proportionality assumptions, in the absence of better information. Harvest by type class is calculated by assuming that it occurs in proportion to the total eligible (merchantable) volume in each type. A similar rule is used to distribute harvest among age classes; harvesting begins with the oldest stand in each type, and any residual harvest request is taken from the remaining eligible age classes in proportion to the existing volume until the total request (for the type) is satisfied.

Where sufficient data exist, the simplistic proportionality assumption for distributing harvest by age class should be modified. Some yield-table models include an option for the user to specify the proportion of harvest to be taken from each age class. Unfortunately, information on the age-distribution of harvest is seldom available for large areas; as a result, the harvest rule used most often in yield-table models is "oldest first." With this approach, harvesting begins in the oldest age class, removing the entire area in each class (if necessary) before moving to the next youngest class. The drawback of this rule is that it imposes a crude form of area regulation that is not typical of existing stands.

A long-term inventory projection model must account for the changes in regional forests brought about through forest management and natural succession (forest dynamics). One of the most important aspects of forest dynamics is new stand establishment after harvest. In SPATS, new stands are separated into two classes: stands regenerating naturally (that is, the new stand type after harvest is determined by conditions on the site, without human intervention) and stands regenerated as an act of forest management. In equation (4), natural regeneration (N_t) is defined as a residual: the total area harvested, less the area actively (artificially) regenerated (P_t).

$$N_t = \left(\sum_j \sum_k H_{jkt}\right) - P_t . \qquad (4)$$

Because the distribution of planting across (source) stand types is not known, N_t is a scalar (it has no type dimension). In equation (5), the type dimension for natural regeneration is estimated from weights derived from the distribution of harvest by stand type.

$$N_{kt} = \left(\sum_j H_{jkt} \Big/ \sum_k \sum_j H_{jkt}\right) N_t . \qquad (5)$$

A different probabilistic structure is required for modeling artificial regeneration. Artificial regeneration (plantation establishment) is the primary forest management activity in SPATS because it reflects the predominant importance of planting in determining the character of the future forest in the South. In addition, public policy frequently focuses on planting by private owners in the South as an instrument for accomplishing long-term supply objectives; therefore, the model user must specify the level of planting for each period.[2] The probability is nonzero that some plantations will fail, however. The area of attempted plantations is deterministic and is an explicit element for policy analysis in SPATS; the results of this management effort are probabilistic.

[2] Three options are used in determining the area planted in each period: a user-specified annual rate for each period, planting set equal to the area harvested, and planting computed from regression-derived equations. See Brooks (1985) for an example of the use of this last option.

The complete regeneration process in SPATS can be summarized:

$$A^{n}_{kt} = N_{kt}\, T_{(k \times k)} \; ; \tag{6}$$

$$A^{a}_{kt} = P_{t}\, \Pi_{(1 \times k)} \; ; \text{ and} \tag{7}$$

$$A_{1,k,t+1} = A^{n}_{kt} + A^{a}_{kt} \; . \tag{8}$$

Equations (6-7) calculate the area entering the first age class by both natural and artificial means. Natural regeneration is computed in equation (6) from a Markov-type transition matrix, T, in which the probability of an acre regenerating into any type is conditioned on the type in existence at the time of harvest. The product of the (1 x k) vector N_{kt} and the (k x k) matrix T is a (1 x k) vector showing the area regenerating naturally into the first age class of each type. A brief description of the Markov process, as applied here, is in appendix 2.

In equation (7), a (1 x k) plantation outcome probability vector, Π, is used to calculate the area entering the first age class of each type as a consequence of plantation effort. In general, most efforts to establish plantations are successful for any owner; the range of "failed" outcomes includes no stand and stands of other type classes (indistinguishable from those of natural origin). Equation (8) is a simple summation that completes the assignment of acres to the first age class.

In equation (3), timber yields are shown to have a time index, as well as age and forest type dimensions; this reflects the expectation that average yields will change over time, demonstrating an "approach to normality." That is, to the extent that yields in time t (for any age and type class) are based on stands with other-than-normal stocking, the yields of these stands are expected to become more "normal" over time. In general, the direction of this approach is from below (in aggregate, forests tend to be understocked), although the principle applies as well to stands with higher than normal stocking. This change in yield is the product of a natural process (stands tend to fully occupy sites); at the same time, it also reflects changes in management practices not modeled explicitly. In both cases, yields must be adjusted over the projection period.

The starting point is a vector of area-weighted average volumes per acre (by age class) for each forest type: y_{jkt}, for t=0. The product of these yield vectors and the initial area vectors (A_{jkt}), summed across all forest types, is the total growing stock at the start of the simulation. Yields are adjusted by assuming that the approach to normality proceeds at a decreasing rate toward a bound. The relationship is

$$p_{jk,t+1} = \alpha_0 + \alpha_1\, p_{jkt} \; ; \tag{9}$$

where p_{jkt} indicates the yield in time t for stands of age j, type k, expressed as a proportion of normal yields, and α_0, α_1 are parameters of the approach to normality

function. The upper bound (the maximum proportion of normal) for any stand is defined by $\alpha_0/(1-\alpha_1)$. Yields for each period are calculated as

$$y_{jkt} = y^n_{jk} p_{jkt} \quad ; \qquad (10)$$

where y^n_{jk} is the normal yield for age j of type k. The proportion of normal is roughly equivalent to an area-weighted, average stocking level for the type class. In SPATS, the proportion of normal at the start of the simulation is constant for all age classes; program options allow the user to specify different rates of change for stands in different age groups (for example, a less rapid approach—or none at all—for older stands).

Two points are important here: first, the proportion of normal at the start of the simulation must reflect actual conditions. This is essentially a matter of model calibration. It can be seen that this calibration can be done with any two of the three pieces of information in equation (10): (a) empirical yields (y_{jkt} for t=0) that, in conjunction with the area distribution, produce the known initial volume; (b) normal yields for the forest type (y^n_{jk}); and (c) an estimate of the proportion of normal (the stocking percent) at the start of the simulation. Empirical yields (average volumes per acre) are available as part of the basic inventory data; p_{jk0} can be estimated from empirical stocking data. Alternatively, normal yields can be specified and p_{jk0} computed as the ratio of empirical and normal yields.

Second, the approach to normality equation must be reasonable in terms of both the rate of approach and the maximum proportion achieved (the upper bound). This is mainly a matter of sensitivity analysis and user judgment because little empirical information concerning the approach to normality is available. (An exception is Chaiken (1939), who estimated that undisturbed (average) loblolly pine stands in the South will increase in stocking 12.5 percent over a 5-year period.) This, too, is a model feature through which users can incorporate assumptions about the yield impact of future management actions not explicitly modeled (the use of genetically improved stock, for example).

Model Validation

Two types of model validation can be considered: structural and empirical. Structural validation appeals to sources that support the form of the model, without reference to specific results (model output). Empirical validation, on the other hand, compares model output to data from alternative sources.

Yield-table projection is a familiar and simple methodology, and no further effort will be made to defend its use as a structure for projecting regional timber inventories. The SPATS model also has structural features in common with forest succession models. By a taxonomy developed by Shugart and West (1980), SPATS can be described as a forest succession model composed of a mosaic of elements, each representing stands of a given age and forest type (and management regime). Unlike most forest succession models, however, changes in this mosaic in SPATS are modeled as being neither purely probabilistic nor simply continuous.

The literature contains examples of forest models that simulate forest succession but do not incorporate human-caused "disturbances" (Shugart and others 1973); succession in this case is a continuous process. Using a probability matrix, Usher (1966) develops a forest model (in which harvesting is recognized), but it is applied only to the problem of determining sustained yield in uneven-aged forests. Aging in SPATS is a continuous process up to the time of harvest; the timing and the extent of the removal of older stands are determined by a model of human (economic) behavior or by assumption, independent of the model of the forest. New stand establishment is mainly, but not entirely, probabilistic. In this combination of natural and human-dependent relations, the structure of SPATS more closely represents the conditions of southern forest development over a long period.

It is impossible to provide empirical validation for a long-term projection model; the model provides estimates of future values that cannot be known. Projections, too, are conditioned on the values of parameters and input data; any evaluation is simultaneously a test of model structure and data. A partial substitute for full-scale empirical validation is provided by starting the simulation at a point as far before the present as data permit; model output can then be compared to historical data. Conceptually, this is the most appealing form of validation; unfortunately, little historical data with which it can be done are available. The basic input data for SPATS are available only for one point in time; historical validation requires equivalent data sets for (at least) one full projection cycle (5 years). Although this type of validation is not possible now, in the future it will be available.

Another kind of validation compares projections made by independently developed models with comparable data sets. Neither model can provide a "more correct" view of the future, but independent forecasts should be consistent. This process is both a structural and an empirical validation, and it is in this context that a comparison of SPATS and TRIM is useful.

Both SPATS and TRIM are yield-table projection models, but they differ in several important respects. Not the least of these differences is the amount of detail used to represent the forests of the region. A bigger model (one with more detail—TRIM in this case) is commonly assumed to produce more reliable results; however, this assumption is seldom subjected to an empirical test. The choice between large and small models should be based on a direct comparison of model characteristics and results; it can be argued (based on Occam's principle, if no other) that the simpler model should be used if there is little or no difference in the value of critical variable(s) projected by the models.[3] Perhaps the most valuable benefit from a comparison of SPATS and TRIM is the opportunity to evaluate the impact of data aggregation (or disaggregation) on timber inventory projections for the Southern United States.

[3] Occam's principle (*"essentia non sunt multiplicanda praeter necessitatem"*) is equivalent to the engineering principle: begin with the simplest approximation, and add new features only as necessary.

Other differences between SPATS and TRIM include the manner in which stands are harvested and assumed to regenerate, and the way in which changes in the forest land base are modeled. In TRIM, the "oldest first" harvesting rule is used, and all harvested stands are assigned initially to the original stand type. In each period, stands (of any age) are subsequently shifted between classes that include both forest type and management intensity. These shifts are user-specified and, in principle, can be made to be equivalent (in results) to the transition probability framework in SPATS. Changes in the forest land base in TRIM are treated similarly; any additions or deletions are accounted for through user-directed shifts. Tedder and others (1987) describe this process in more detail.

In spite of these differences, the models are similar in most other respects, and it is reasonable to compare their output. With equivalent data sets and assumptions, projections of broad aggregates (total growing stock, for example) by the two models should differ very little. Data for SPATS were taken from TRIM basic resource unit files and aggregated. Site classes, stocking levels, and management intensities were combined in area data; empirical yields were calculated as area-weighted averages. Removals from growing stock (specified by owner and region) are identical in the two simulations; data shown in TRIM allowable cut unit (softwood) reports were used in the SPATS projection.[4] Planting is prespecified in the SPATS projection; actual data for 1980-84 are used, and in subsequent periods data are based on trends from the 1980-84 average.

Projected values for softwood growing stock are shown in figure 1; projected values for softwood growth are shown in figure 2. Projections are shown for two owners (forest industry and nonindustrial private) in each of two regions (Southeast and South Central). In three of four projections, the SPATS projections closely track those made with TRIM. The maximum difference in projected growing stock in any year in these three projections is less than 10 percent. The exception to this close tracking is the South Central forest industry where SPATS projects a rapid increase in growing stock after the year 2000. The TRIM projection for the South Central forest industry is somewhat puzzling, especially when compared with the TRIM projection for forest industry in the Southeast. Over the period 1975-84, forest industry owners in the South Central region established pine plantations at a faster rate than their counterparts in the Southeast. The SPATS projection of growing stock eventually reflects this activity, but the TRIM projection apparently does not. Projected values for softwood growth are also close, again with the exception of the South Central forest industry.

[4] The TRIM data are from unpublished output titled "Run 17 SO Base Round 3" and dated 86/07/18; reports on file at the Macroeconomics of U.S. and International Trade Project, USDA Forest Service, Pacific Northwest Research Station, Portland, Oregon.

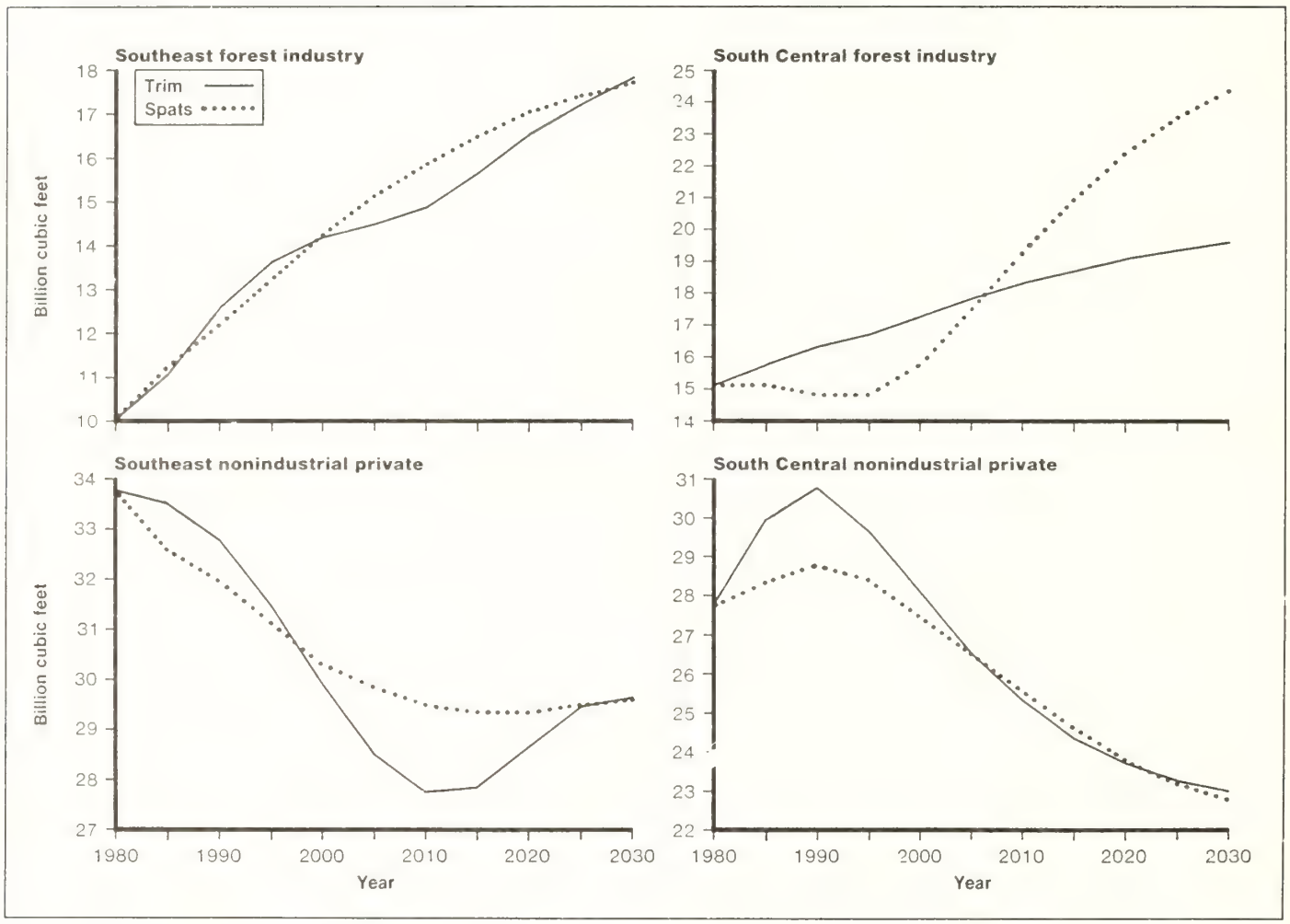


Figure 1—Projections of softwood growing stock by region and owner, 1980 to 2030, made by TRIM and SPATS.

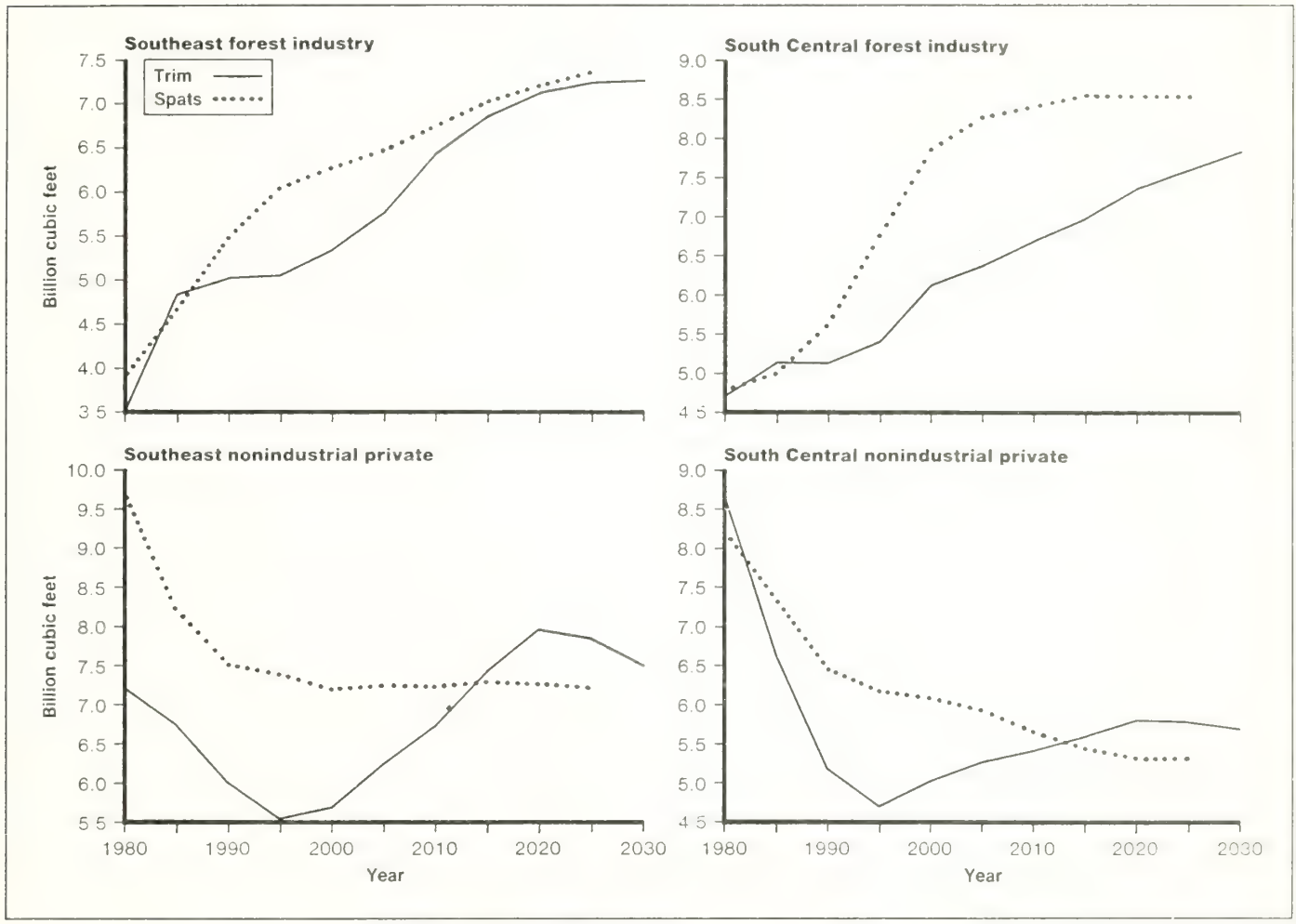


Figure 2—Projections of periodic softwood growth by region and owner, 1980 to 2030, made by TRIM and SPATS.

Theil's (1966) inequality coefficient was computed for each pair of simulations by assuming that the TRIM projections of softwood growing stock are the "actual" data, and the SPATS projections are the predicted data. A value of zero indicates a perfect fit; a value of 1 can be obtained by predicting a constant value. Results are shown in table 1. The sources of the forecast error are also shown as proportions of the total error. The quantitative measures shown in table 1 confirm the graphic comparisons in figure 1.

To conclude from this comparison that one model is more "correct" than the other (or, because of the similarity, that both are correct) is not appropriate. Nevertheless, that these two models, using similar but not identical assumptions, and organized quite differently, come to similar conclusions about the time path of softwood growing stock for private owners in the South, is somewhat reassuring. With the exception of the South Central forest industry, differences between growing stock projections produced by SPATS and those produced by TRIM will have very little impact on estimates of short-term timber supply in TAMM.

Some inferences can be drawn about data aggregation and model simplicity from these results. The SPATS projections are similar to those from TRIM in large part because the extensive detail in TRIM is the result of (or at least is supported by) simple proportionality assumptions. For example, although there are sufficient data to classify forest area in TRIM by forest type, site class, stocking level, and management intensity, little if anything is known about the distribution of harvest across these dimensions of the forest. Therefore, harvest is assumed to be proportional to the area or volume in each dimension. Under these circumstances, however, to use aggregated area data and weighted average yield data is algebraically equivalent; as a result, SPATS projections are similar to those produced by TRIM.

In some applications, the extensive detail contained in TRIM is desirable, if not required. That TRIM is flexible in terms of the detail it maintains is also important to keep

Table 1—Comparison of TRIM and SPATS projections of softwood growing stock, by use of Theil's inequality coefficient

Region and owner	Inequality coefficient	Sources of forecast error[1/]		
		Bias	Variance	Covariance
Southeast:				
Forest industry	0.4249	0.0013	0.0208	0.9779
Nonindustrial private	0.6660	0.0000	0.3900	0.6100
South Central:				
Forest industry	1.9585	0.2659	0.4121	0.3220
Nonindustrial private	0.5298	0.0014	0.7058	0.2928

[1/] Expressed as a proportion of the total error.

in mind. In fact, aggregation procedures for TRIM that will result in an inventory structure similar to that used in SPATS can be defined. In some applications, however, the detail that TRIM is able to provide seems to be of little benefit; for example, long-term timber market simulations made in conjunction with TAMM.

Timber inventory model size and data requirements must be kept proportional to their relative importance; however, the development of regional inventory models should not be arrested at the complexity of SPATS. As data improve, more detailed models will be able to provide more robust projections. The argument made here, and supported to some extent by the direct comparison of SPATS and TRIM, is for a careful assessment of the question of appropriate scale and the amount of detail to include in regional timber inventory simulation models.

Literature Cited

Adams, Darius M.; Haynes, Richard W. 1980. The 1980 softwood timber assessment market model: structure, projections, and policy simulations. Forest Science Monogr. 22. 64 p.

Adams, Darius M.; Haynes, Richard W.; Dutrow, George; Barber, Richard; Vasievich, James. 1982. Private investment in forest management and the long-term supply of timber. American Journal of Agricultural Economics. 64: 232-241.

Alig, Ralph J.; Lewis, Bernard J.; Morris, Paul A. 1984. Aggregate timber supply analysis. Gen. Tech. Rep. RM-106. Fort Collins, CO: U.S.Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 49 p.

Boyce, Stephen G.; Knight, Herbert A. 1979. Prospective in-growth of southern pine beyond 1980. Res. Pap. SE-200. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest and Range Experiment Station. 48 p.

Brooks, David J. 1985. Public policy and long-term timber supply in the South. Forest Science. 31: 342-357.

Chaiken, L.E. 1939. The approach of loblolly and Virginia pine stand toward normal stocking. Journal of Forestry. 37: 866- 871.

Larson, Robert; Goforth, Marcus. 1974. TRAS: a timber volume projection model. Tech. Bull. 1508. Washington, DC: U.S. Department of Agriculture, Forest Service. 15 p.

Shugart, H.H., Jr.; West, D.C. 1980. Forest succession models. BioScience. 30: 308-313.

Shugart, H.H., Jr.; Crow, T.R.; Hett, J.M. 1973. Forest succession models: a rationale and methodology for modeling forest succession over large regions. Forest Science. 19: 203-212.

Tedder, P. L.; LaMont, Richard N.; Kincaid, Jonna C. 1987. The timber resource inventory model (TRIM): A projection model for timber supply and policy analysis. Gen. Tech. Rep. PNW-GTR-202. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 82 p.

Tedder, Philip L.; Schmidt, James S.; Gourley, Jonna. 1980. TREES: Timber resource economic evaluation system. Vol. 1. A user's manual for forest management and harvest scheduling. Res. Bull. 31a. Corvallis, OR: Oregon State University, Forest Research Laboratory. 81 p.

Theil, Henri. 1966. Applied economic forecasting. Amsterdam: North-Holland. 325 p.

U.S. Department of Agriculture, Forest Service. 1982. An analysis of the timber situation in the United States 1952-2030. For. Resour. Rep. 23. Washington, DC. 499 p.

U.S. Department of Agriculture, Forest Service. 1987. The South's fourth forest. For. Resour. Rep. Washington, DC. (Review draft.)

Usher, M.B. 1966. A matrix approach to the management of renewable resources, with special reference to selection forests. Journal of Applied Ecology. 3: 355-367.

Van Loock, H.; Hafley, W.; King, R. 1973. Estimation of agriculture-forestry transition matrices from aerial photographs. Southern Journal of Agricultural Economics. 5:147-153.

Appendix 1
Operation Notes

Spats was written in the American National Standards Institute (ANSI) standard FORTRAN-77 language; it has been compiled and executed on a Control Data Corporation (CDC) Cyber 170/720 mainframe computer, and on IBM-PC-compatible microcomputers.[1] Source code and sample data sets are available from David J. Brooks, P.O. Box 3890, Portland, Oregon 97208. The SPATS model contains 10 subroutines and a program segment; when SPATS is used in conjunction with TAMM, the program segment is replaced by subroutine calls within the main control segment of TAMM. Subroutine names are shown in table 2, along with a brief description of subroutine operations. Figure 3 illustrates the sequence of operations in SPATS and the flow of information between SPATS and TAMM. The SPATS model can also be operated as a "stand-alone" model; in this case, annual removals data must be provided as an additional data file.

Two output files are created by SPATS. The primary output file is titled "SPATOUT" and is addressed as unit 12. This file contains simulation summary tables (always produced) and any other program output selected by the user (table 3). Output file "ANNUAL" (unit 7) contains a one-line report for each owner, in each year of the simulation. This file can be sorted to produce a time series of annual estimates of growing stock for each owner.

Program output options (included as data items in input file TAPE1) are shown in table 3. This table also includes information on user options for setting the manner in which plantation establishment is determined.

[1] The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the Department of Agriculture of any product or service to the exclusion of others that may be suitable.

Table 2—Subroutines in SPATS

Subroutine	Operation
SPTSIN	Data input, reads from file TAPE1.
SPTSGD	Growth-drain model, estimates annual change in growing stock; calls SPATS every 5th year.
SPATS	Control for the "full model"; calculates periodic yields; calls all remaining subroutines (except SPTSUM) in sequence.
ACHNG	Calculates area change.
REMOVE	Computes net removals of growing stock, given timber supply.
HRVPV	Thins and harvests the forest; final harvest is proportional to volume.
LEASE	Thins and harvests leased land.
REGROW	Regenerates and grows the forest.
VOLCAL	Computes area and volume statistics.
SPTSUM	Writes simulation summary tables; called from TAMM, or emulator.

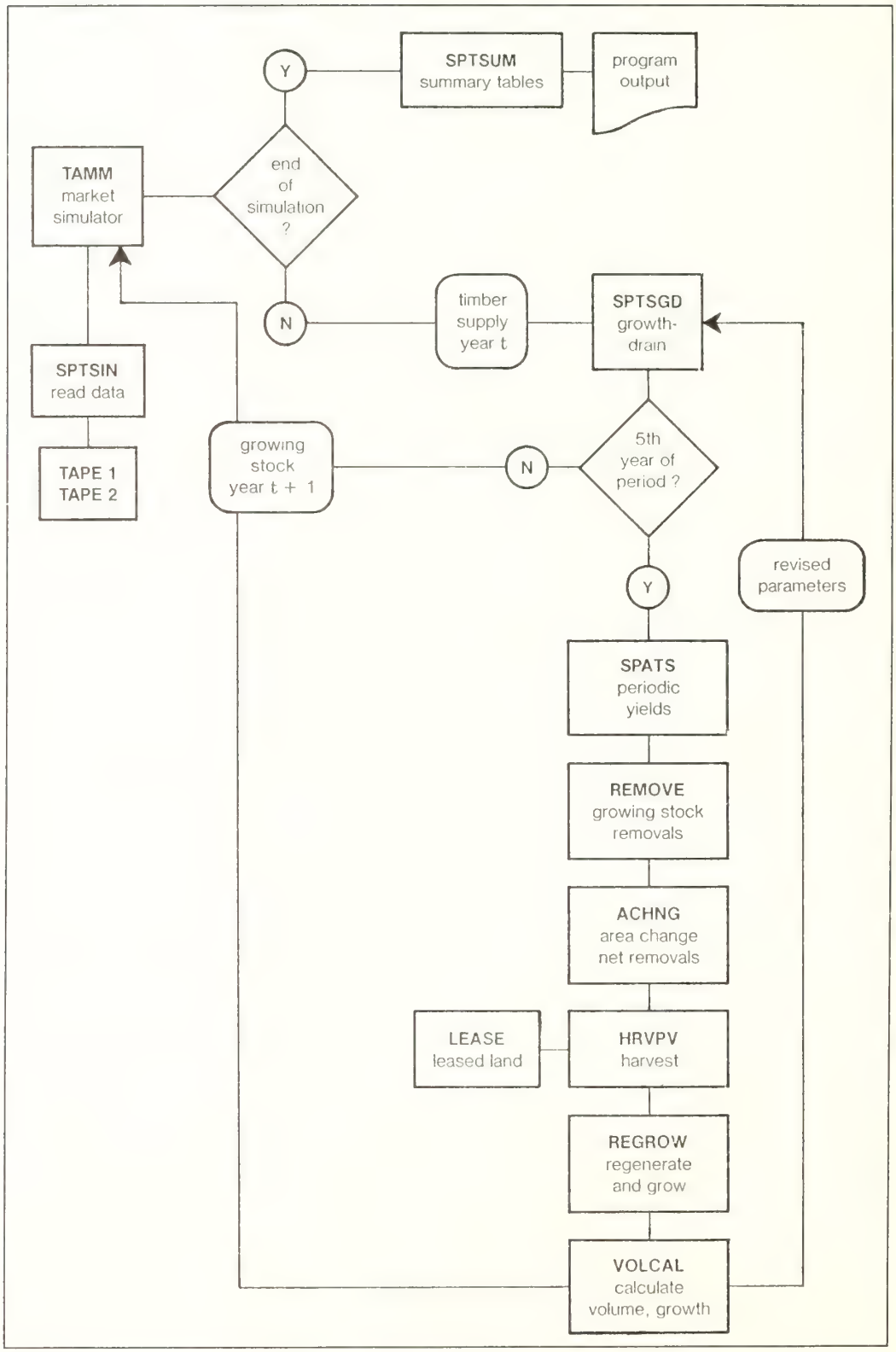


Figure 3—Sequence of operations and flow of information in SPATS.

Table 3—SPATS output options

Variable	Value	Result
IPRINT	0	Short form of output, summary tables only
	1	Full report in every period
IWRITE	0	No echo of input data
	1	Echo input data
IPLANT	0	Planting prespecified, read as ACRPLT(I)
	1	Planting computed from response equations
	2	Planting set equal to annual harvest

Appendix 2
The Stationary Markov Regeneration Model

The forest is characterized by stands of 1,...,K different forest types (where K indicates the total number of types represented). When stands of any type (k) are harvested in time t and allowed to regenerate naturally, they can remain in type k or change to one of the other types. The probability that a stand harvested from type k will regenerate as type m (where m may equal k) is defined as ν_{km}. This is a stationary transition process if ν_{km} does not change over time. The process is also said to be Markovian if this transition probability does not depend on the path by which the stand reached type k.

These transition probabilities have the following additional properties:

$$\nu_{km} \geq 0 \quad \text{for all k,m; and} \tag{11}$$

$$\sum_{m} \nu_{km} = 1 \quad \text{for all k.} \tag{12}$$

The matrix T in equation (6) is composed of the elements ν_{km}; equation (11) states that all elements are nonnegative, and equation (12) that the rows of T sum to one.

Forest types in SPATS are states in a finite-state Markov system. Ordinarily in such a system, the n-step transition probability can be computed by (n) successive squarings of the transition matrix. Because of the properties stated in equations (11-12), the consequence of this self-multiplication is that the row vectors converge to values that define the steady-state condition for the system.

In the natural regeneration transition matrix defined here, however, the system is incomplete, and the n-step transition probability that results from this computation is not valid. Consider, for example, the transition probability matrix in table 4. This is an expansion of data shown in appendix 4 (the rows added for hardwood and non-stocked create a square matrix). The "steady-state" probabilities that result from successive squaring of this matrix are also shown in table 4.

Table 4—Natural regeneration transition probabilities and "steady-state" probabilities

	Destination				
	Pine[1/]		Oak-pine	Hardwood	Nonstocked[2/]
Source	Natural	Plantation			
Pine:[1/]					
Natural	0.40	0.0	0.25	0.30	0.05
Plantation	0.30	0.0	0.35	0.30	0.05
Oak-pine	0.05	0.0	0.15	0.80	0.0
Hardwood	0.0	0.0	0.10	0.90	0.0
Nonstocked	0.0	0.0	0.05	0.05	0.90
Steady-state probabilities[3/]	0.0089	0.0	0.1064	0.8803	0.0044

[1/] Natural = pine stands of natural origin; plantation = planted stands.

[2/] Source stand type identity is retained.

[3/] Convergence was reached after 7 transition steps.

This regeneration system is incomplete because pine plantations are introduced into the system in each period through artificial regeneration, and stands of all types are candidates for planting. When plantations are harvested, if they are allowed to regenerate naturally, they will follow the transition paths indicated in table 4. The probability, however, that stands in any type will regenerate to plantations depends on management decisions. In the probability structure shown in table 4, plantation establishment is deterministic, although it is "passed through" a separate probability framework (shown in table 5).

Table 5—Plantation outcome probabilities[1/]

	Stand type resulting from planting				
	Pine[2/]		Oak-pine	Hardwood	Nonstocked
Owner group	Natural	Plantation			
Forest industry	0.096	0.800	0.089	0.0	0.015
Nonindustrial private	0.097	0.700	0.156	0.0	0.047

[1/] Data are from appendix 4.

[2/] Natural = pine stands with yields equivalent to those of natural origin; plantation = successful plantations.

Appendix 3
Description of Variables

A partial dictionary of variables used in SPATS follows; included are all items contained in the two data files that must be created by the user. No owner index is indicated for any variable; data for each owner are stored in direct access files with records identified by region and owner indexes. Annotated sample data files are shown in appendix 4.

Variable name	Description
ACRE(J,K)	Softwood forest area by age (J=0,19) and stand type (K=1,3)
ACRHD	Area of hardwood stands
ACRLS(J,K)	Area of forest land leased by forest industry (K=1,2)
ACRPLT(I)	Area planted in period I (I=1,11)
AVGSVH	Average softwood volume in hardwood stands
ANITCP	Intercept term for the approach to normality function
ANRM(I)	Proportion of normal yield in period I
ANSLOP	Slope term for the approach to normality function
AREALS	Total area leased by forest industry from nonindustrial
AREA0	Total (initial) forest area
BETA(36,8)	Array through which estimate of growing stock is passed to TAMM
BETAP(J)	Parameters for the planting response equation (J=0,5)
BFCF(J)	Board foot/cubic foot ratio, by age class (J=0,19)
BFCF0	Average board foot/cubic foot ratio
CFACT	Growth-drain, available cut adjustment factor (CFACT >0.20)
COMARA(I)	Total commercial forest land area at the end of period I
CRPIDL(I)	Idle cropland available for natural regeneration
GCRAT(0)	Startup value, growth/cut ratio
GPCNT0	Startup value, growth percent
GSINV0	Startup value, total softwood growing stock
GSMRCH0	Startup value, merchantable softwood growing stock
HARDLS	Hardwood forest type, area leased
HARDMIN	Minimum area of hardwood forest type
I	Index indicating the simulation period (5-year interval)
IPLANT	Flag indicating type of planting computation
IPRINT	Flag indicating output option
IWRITE	Flag indicating output option
ISTRT	Starting year for the simulation
J	Index indicating age class (J=0 is nonstocked)
JFULAP	Maximum age class for full approach to normality
JHLFAP	Maximum age class for half approach to normality
JMN(K)	Minimum harvest age, by softwood type
JMNT(K)	Minimum thinning age, by softwood type
JMX(K)	Maximum age class, by softwood type
K	Index indicating softwood forest type
L	Index indicating owner group
LAGEND	Flag indicating the use of lagged endogenous variables, planting equations
LAGPAY	Flag indicating the number of lags for public payments, planting equations
LAGX(N)	Flags indicating lags on right-hand-side variables, planting equations
LSMRCH0	Initial merchantable softwood volume, leased land
LSVOL0	Initial total softwood volume, leased land
NNPER	Number of periods in the simulation
NNREG	Index for region
NNUM	Index indicating the number of region-owners
NRGO	Index for owner group
OO	Unit number for primary output file (assumed to be 12)

Variable name	Description
OWNER	2-character identifier for owner group
PAI0	Initial periodic annual increment
PINE0	Initial area in softwood types
PLR(I)	Proportion of growing-stock removals left as logging residues in period I
POR(I)	Other removals of growing stock in period (proportion)
PPRG	Proportion of idle cropland regenerating each period
PPT(K)	Plantation outcome probabilities (K=1,4)
PRG(KS,KD)	Natural regeneration transition probabilities; KS(source type)= 1,3; KD (destination type)=1,5
PRNGS(I)	Proportion of roundwood taken from nongrowing-stock sources in period I
PRPM	Proportion of merchantable material used in area change
PTHYLD(J,K,I)	Thinning yields (area proportion times volume proportion) by age (J), stand type (K), and period (I)
REGION	2-character identifier for region
RNS(K)	Proportion of nonstocked acres regenerated, by softwood type
REMOVE(36,4)	Array through which removals are passed from TAMM to SPATS
STITLE	80-character data identifier
STAND0(K)	Initial area by stand type
SYLD(J,K)	Empirical yields, by age and softwood type (K=1,3)
SYLDN(J,K)	Normal yields, by age and softwood type
XVAR((J,I)	Right-hand-side variables for planting equations, by period

Appendix 4
Annotated Data Files

TAPE1 (unit 1)

TAPE1 contains all data except annual removals and is read at startup by subroutine SPTSIN. The general structure is:

N (the number of region-owner "blocks")
BLOCK 1 (Southeast forest industry)
BLOCK 2 (Southeast nonindustrial private)
BLOCK 3 (South Central forest industry)
BLOCK 4 (South Central nonindustrial private)

The ordering of the blocks does not matter as long as the indexes in each block are correct. Single-owner simulations can be made when leased acres are not explicit; otherwise, the simulation requires a pair of owners for each region: forest industry and nonindustrial private. Variable names and dimensions are shown in brackets [ ] for explanation. See appendix 3 for a brief description of the variables.

```
[NNUM]
4
[STITLE]
LR  46  REMOVALS / ALIG TOTAL AREA PROJECTIONS / TRIM AGE DATA /
[REGION, OWNER]
SEFI
[NNREG,  NRGO,  L]
10  1  1
[ISTRT, NNPER, OO, IPRINT, IPLANT, IWRITE]
1980  10  12  0  2 0
[(JMNT(K),  JMN(K),  JMX(K),  K=1,3)]
3  5  19  3  5  11  6  8  19
```

```
[((ACRE(J,K),   K=1,3),   J=0,19)]
      0.00          0.00          0.00
    410.59       2018.70        322.17
    179.66       1452.60        175.71
    203.45       1006.48        128.06
    386.03       1052.62        106.05
    594.65        521.86         83.02
    537.30         88.00        115.17
    584.73         32.58        103.13
    442.01         15.95        116.39
    244.93          5.20        105.82
    241.90          3.62         76.44
    147.86          0.00         75.33
    142.35          0.00         29.16
     63.57          0.00         28.02
     25.73          0.00         26.49
     17.38          0.00         18.37
     21.27          0.00         11.24
     12.73          0.00         12.06
     16.94          0.00         16.34
      0.00          0.00          0.00
[ACRHD]
         5678
[((ACRLS(J,K), J=0,19), K=1,2)]
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
[HARDLS]
00.0
[((SYLD(J,K), J=0,19), K=1,3)]
 .021   .156   .416   .676   .910  1.118  1.274  1.417  1.529  1.612
1.703  1.770  1.820  1.867  1.898  1.924  1.945  1.960  1.971  1.976
 .031   .156   .364   .884  1.352  1.768  2.028  2.158  2.262  2.288
2.314  2.314  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
 .052   .099   .130   .195   .293   .366   .435   .503   .567   .626
 .680   .728   .772   .806   .834   .858   .876   .886   .889   .889
[AVGSVH]
 .123
[((SYLDN(J,K), J=0,19), K=1,3)]
 .040 .300 .800 1.300 1.750 2.150 2.450 2.725 2.940 3.100
3.275  3.405  3.500  3.590  3.650  3.700  3.740  3.770  3.790  3.800
 .060   .300   .700  1.700  2.600  3.400  3.900  4.150  4.350  4.400
4.450  4.450  .00 .00 .00 .00 .00 .00 .00 .00
 .100   .190   .250   .375   .564   .704   .837   .967  1.091  1.204
1.307  1.401  1.484  1.551  1.604  1.650  1.685  1.705  1.710  1.710
```

```
[(((PTHYLD(J,K,I), J=3,8), K=1,3), I=1,12)]
 .066 .066 .109 .0 .0 .0 .109 .124 .124 .0 .0 .0 .0 .0 .0 .05 .05 .0
 .066 .068 .111 .0 .0 .0 .109 .126 .126 .0 .0 .0 .0 .0 .0 .05 .05 .0
 .066 .070 .113 .0 .0 .0 .109 .128 .128 .0 .0 .0 .0 .0 .0 .05 .05 .0
 .066 .072 .115 .0 .0 .0 .109 .130 .130 .0 .0 .0 .0 .0 .0 .05 .05 .0
 .066 .074 .117 .0 .0 .0 .109 .132 .132 .0 .0 .0 .0 .0 .0 .05 .05 .0
 .066 .076 .119 .0 .0 .0 .109 .134 .134 .0 .0 .0 .0 .0 .0 .05 .05 .0
 .066 .078 .121 .0 .0 .0 .109 .136 .136 .0 .0 .0 .0 .0 .0 .05 .05 .0
 .066 .080 .123 .0 .0 .0 .109 .138 .138 .0 .0 .0 .0 .0 .0 .05 .05 .0
 .066 .082 .125 .0 .0 .0 .109 .140 .140 .0 .0 .0 .0 .0 .0 .05 .05 .0
 .066 .084 .127 .0 .0 .0 .109 .142 .142 .0 .0 .0 .0 .0 .0 .05 .05 .0
 .066 .086 .129 .0 .0 .0 .109 .144 .144 .0 .0 .0 .0 .0 .0 .05 .05 .0
 .066 .088 .131 .0 .0 .0 .109 .146 .146 .0 .0 .0 .0 .0 .0 .05 .05 .0
[((PRG(KS,KD), KD=1,5), KS=1,3)]
 .40 .00 .25 .30 .05
 .30 .00 .35 .30 .05
 .05 .00 .15 .80 .00
[(PPT(K), K=1,4)]
 .096 .800 .089 .015
[(RNS(K), K=1,3), PPRG, PRPM]
 .15 .00 .25 .15 .75
[(BETAP(J), J=0,5)]
56.6096 6.7310 0.0 .000049 .4596 -35.684
[LAGPAY, LAGEND, (LAGX(J), J=1,5)]
0 1 0 0 1 0 0
[(PRNGS(I), PLR(I), POR(I), ANRM(I), COMARA(I), I=1,11)]
 .050667 .057 .01 .545 17725
 .052600 .052 .01 .570 18429
 .054600 .047 .01 .595 18611
 .055000 .043 .01 .620 18701
 .055000 .039 .01 .645 18790
 .055000 .037 .01 .670 18853
 .055000 .034 .01 .695 18915
 .057000 .032 .01 .720 18982
 .059500 .031 .01 .745 19049
 .060000 .030 .01 .770 19059
 .060000 .030 .01 .795 19068
[ANSLOP, ANITCP, JFULAP, JHLFAP]
 .945 .055  6  10
[((XVAR(J), J=1,5), ACRPLT(I), CRPIDL(I), I=1,11)]
26 3.09 290177.0 312.447 0.00 370.00 2562.10
28 3.18 0.00 0.00 0.00 370.00 2562.10
30 3.28 0.00 0.00 0.00 375.00        0.00
30 3.38 0.00 0.00 0.00 380.00        0.00
30 3.48 0.00 0.00 0.00 385.00        0.00
30 3.58 0.00 0.00 0.00 390.00        0.00
30 3.68 0.00 0.00 0.00 395.00        0.00
30 3.78 0.00 0.00 0.00 400.00        0.00
30 3.88 0.00 0.00 0.00 400.00        0.00
30 3.98 0.00 0.00 0.00 400.00        0.00
30 4.08 0.00 0.00 0.00 400.00        0.00
30 4.18 0.00 0.00 0.00 400.00        0.00
[GSINV0, GSMRCH0, PAI0, GPCNT0, AREA0, PINE0,(STAND0(K), K=1,4)]
8804.58 4763.73 784.49 .08909 15059.99 10356.83 3943.69 4765.15
1647.98 4703.16
```

```
[(BFCF(J), J=0,19)]
 .500 1.100 1.700 2.100 2.500 2.835 3.175 3.400 3.675 3.900
4.100 4.210 4.325 4.400 4.410 4.450 4.450 4.400 4.375
[HARDMIN]
3800.0
[LSVOL0, LSMRCH0, AREALS, BFCF0, GCRAT(0), CFACT]
1146.49 599.23 1953.40 2.940 1.394 .28
[end of block 1]
```

Roundwood removals data (unit 2)—In the "stand-alone" version of SPATS, removals data are read from unit 2, in a program segment called TAMMEM. The growth-drain subroutine SPATSGD is called for each year of the simulation, and the removals information read is passed in common block TRAS in the array REMOVE( ). Every 5th year of the simulation, subroutine SPATS is called by SPATSGD, and accumulated removals are passed for each owner and region. Variable names and dimensions are shown in brackets [ ] for explanation. See appendix 3 for a description of variables.

```
[header identifying the data set]
TRIM DATA
[TSTRT, TEND, NNUM]
1980 2030 4
[ REMOVE(N,T), N=1,NNUM, T=TSTRT,TEND ]
     461.824      1318.272      717.442      1192.471    [ 1980 ]
     494.533      1356.485      728.710      1206.584
     509.172      1324.551      769.863      1242.128
     545.086      1356.701      898.611      1327.097
     594.514      1428.603      925.311      1332.999
     623.273      1432.743      895.428      1312.608    [ 1985 ]
        .            .             .            .           .
        .            .             .            .           .
        .            .             .            .           .
    1494.000     1659.000      1503.000     1372.000    [ 2030 ]
```

Brooks, David J. 1987. SPATS: a model for projecting softwood timber inventories in the Southern United States. Res. Pap. PNW-RP-385. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 23 p.

The yield-table projection method for modeling the development of regional timber inventories is outlined, and its application to softwood timber types in the Southern United States is described. Problems of simulating forest management practices and natural succession are discussed. A computer model that projects softwood timber inventories using yield-table projection and stand regeneration using a Markovian probability structure is presented. The methodology and projections of this model are compared with alternative approaches to predicting future timber inventories in this region.

Keywords: Yield-table projection, inventory models, softwood timber supply, South.

The **Forest Service** of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing nation.

The U.S. Department of Agriculture is an Equal Opportunity Employer. Applicants for all Department programs will be given equal consideration without regard to race, color, sex, religion, or national origin.

Pacific Northwest Research Station
319 S.W. Pine St.
P. O. Box 3890
Portland, Oregon 97208

October 1987

U.S. Department of Agriculture
Pacific Northwest Research Station
319 S.W. Pine Street
P.O. Box 3890
Portland, Oregon 97208

BULK RATE
POSTAGE +
FEES PAID
USDA-FS
PERMIT No. G-40

Official Business
Penalty for Private Use, $300

do NOT detach label

United States
Department of
Agriculture

Forest Service

Pacific Northwest
Forest and Range
Experiment Station

Research Paper
PNW-RP-386

TENNESSEE'S Forest Products Industry: Performance and Contribution to the State's Economy, 1970 to 1980

Wilbur R. Maki, Con H Schallau, Bennett B. Foster, and Clair H. Redmond

Abbreviations

States

AL	Alabama
AR	Arkansas
FL	Florida
GA	Georgia
KY	Kentucky
LA	Louisiana
MS	Mississippi
NC	North Carolina
OK	Oklahoma
SC	South Carolina
TN	Tennessee
TX	Texas
VA	Virginia
SO	South
US	United States

Industries

FPI	Forest Products Industry
LWP	Lumber and Wood Products
PAP	Paper and Allied Products
WF	Wood Furniture

Authors

WILBUR R. MAKI is a professor, University of Minnesota, Department of Agricultural and Applied Economics, St. Paul, Minnesota 55108. CON H SCHALLAU is a research economist at the Pacific Northwest Research Station, Forestry Sciences Laboratory, 3200 Jefferson Way, Corvallis, Oregon 97331. BENNETT B. FOSTER and CLAIR H. REDMOND are, respectively, forest economist and economist, USDA Forest Service, Southern Region, State and Private Forestry, 1720 Peachtree Road N.W., Atlanta, Georgia 30367.

Abstract

Maki, Wilbur R.; Schallau, Con H; Foster, Bennett B.; Redmond, Clair H. 1987. Tennessee's forest products industry: performance and contribution to the State's economy, 1970 to1980. Res. Pap. PNW-RP-386. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 22 p.

The forest products industry is one of Tennessee's basic industries; in 1980, for example, it accounted for about 1 of every 12 basic jobs. Furthermore, Tennessee was one of the majority of Southern States in which the forest products industry improved its competitive position during the 1970's. In 1977, productivity growth of the paper and allied products segment far exceeded the average for the forest products industry as well as the average for all industries.

Keywords: Forest products industries, economics (forest products industries), employment (forest products industries), Tennessee.

Preface

This report briefly describes Tennessee's forest products industry—its composition, location, evolution, and relation to economic activity elsewhere in the State, the South, and the Nation.

This is one in a series of reports for each of the 13 Southern States. These reports are companions to an analysis of the interregional competition in the forest products industries of the South and the Pacific Northwest.

Estimates of employment and earnings shown in this report were derived from U.S. Department of Commerce data. All references to dollar amounts are in constant 1977 dollars.

Highlights

- The forest products industry is one of Tennessee's basic industries; that is, it exports products and by doing so brings in new dollars to support economic growth and development. In 1980, the forest products industry accounted for about 1 of every 12 of Tennessee's basic jobs.

- Tennessee's forest products industry is comprised of paper and allied products, lumber and wood products (not including mobile homes), and wood furniture manufacturing. Employment was almost equally distributed among the three segments in 1980, but paper and allied products accounted for nearly half of the total earnings. Employment decreased in the wood furniture segment between 1970 and 1980 but increased in the other two segments.

- In 1977, paper and allied products had the largest share of the $1.1 billion of value added by Tennessee's forest products industry.

- In addition to having above-average growth in employment, the forest products industry increased in value added between 1972 and 1977. The value added increased by 10 percent, but only on the strength of paper and allied products—value added by the wood furniture and the lumber and wood products segments actually decreased.

- The rate of growth in average earnings was about the same for Tennessee's forest products industry as for the Nation, but somewhat less than the average for the South. The rate of change for wood furniture was considerably less than that of the entire forest products industry in the United States and the South.

- Paper and allied products had, by far, the highest productivity in Tennessee's forest products industry. Productivity per worker hour was more than twice the average for the State's forest products industry. Productivity in the wood furniture and lumber and wood products segments—which were low to begin with—decreased between 1972 and 1977.

- Tennessee was one of the majority of Southern States in which the forest products industry improved its competitive position during the 1970-80 period.

- Between 1972 and 1977, growth in productivity of paper and allied products (43 percent) far exceeded the average for the forest products industry as well as the average for all industries in the Nation. Productivity in both of the other segments declined.

Contents

1 **The Forest Products Economy of Tennessee**
1 The Work Force
2 Components of the Economic Base
4 Geographical Importance of the Forest Products Industry
5 Composition of the Forest Products Industry
6 Average Annual Earnings per Worker
7 Value Added by the Forest Products Industry
8 Capital Productivity
9 **The Forest Products Industry in the South**
9 Importance of the Industry Across the South
10 Industry Composition
12 Growth of Employment
13 Average Annual Earnings
14 Shift in Employment and Earnings
16 Value Added by the Forest Products Industry
17 Capital Productivity
18 **Acknowledgment**
18 **Appendix 1**
18 Tables
22 **Appendix 2**
22 Tennessee Counties by Sub-State Planning and Development Districts

The Forest Products Economy of Tennessee

The Work Force

Tennessee's estimated full- and part-time work force in 1980 was comprised of an estimated 2.2 million employees and proprietors (see appendix table 1 for sources of employment and earnings data). Tennessee's work force grew faster between 1970 and 1980 than did the national average (24.8 versus 22.3 percent). Total earnings--wage and salary payments and proprietorial income--grew much faster than the national average. Measured in constant 1977 dollars, the State's earnings increased by 35.2 percent compared with 27.4 percent for the Nation. As can be seen in the following tabulation, manufacturing, services, retail trade, and State and local government were the State's four largest employer categories, as they were for the Nation.

	Percent of total employment 1980	
Employers	**Tennessee**	**U.S.**
Major industries:		
Manufacturing (including the forest products industry [1])	23.4	19.2
Services	15.6	18.2
Retail trade	12.6	14.2
State and local government	12.6	12.6
Self-employed	6.8	6.6
Agriculture	6.8	4.4
Wholesale trade	5.2	5.0
Transportation	4.1	4.8
Finance, insurance, and real estate	3.8	5.0
Construction	3.7	4.1
Federal civilian	3.5	2.8
Federal military	1.6	2.3
Mining	0.4	1.0
Total [2]	100.0	100.0

[1] The forest products industry has three segments: (1) lumber and wood products (SIC 24), except mobile homes (SIC 2451); (2) wood furniture manufacturing (SIC 2511, 2512, 2517, 2521, 2541); and (3) paper and allied products (SIC 26).

[2] Sum of parts may not equal totals because of rounding.

Components of the Economic Base

Along with total employment, there is another and perhaps more important way to judge an industry's contribution to Tennessee's economy. For the State's economy to grow and develop, it must attract new dollars so residents can buy goods and services produced elsewhere. The industries that export products and services beyond local boundaries (that is, to elsewhere in the State, to other States, and to the world) and bring in new dollars constitute the area's economic base. Generally speaking, most manufacturing employment is classified as economic base (or basic); service or residentiary employment (for example, barber shops, realty firms, schools, and local government) is primarily geared to producing for local needs. Some services may, however, be basic. Federal civilian employment provides national services (for example, ordnance and natural resource management) for all the Nation's citizens, and taxpayers outside Tennessee provide financial support for this activity. Federal civilian, therefore, qualifies as one of Tennessee's basic industries.

Residentiary employment and its earnings are supported by the economic base. Money flowing into a State for goods and services sold to businesses, governments, and households outside the State provide the income that reimburses wage earners and the self-employed for their services. This income is largely spent for locally available goods and services. The economic growth of an area is thus dependent on the success of its economic base; the residentiary activities—which serve businesses, government, and household residents of the State—enhance the business climate and the quality of life of these residents.

We used the excess employment and excess earnings techniques to identify the industries that comprise Tennessee's (or a sub-State district's) economic base. This approach accepts the national distribution of employment among industries and its earnings as the norm. Any industry with employment in excess of this norm is considered to be producing for export markets outside the State (or sub-State district) and is part of Tennessee's economic base, provided that the proportion of full-time employment and the productivity of this employment is the same as that for the rest of the Nation. Because of the large amount of part-time workers in farming, for example, the total earnings of this employment is used as an alternative measure of industry dependency. Although the percentage distribution of the total earnings differs sharply from the total employment distribution, the two measures yield consistent results in that earnings data adjust for the above-average level of part-time employment in a basic industry like farming.

In this study, the percentage of Tennessee's excess employment and earnings served as an indicator of the State's dependency on a particular industry for generating new dollars from outside the State (table 2 shows how excess employment and industry dependency indicators for Tennessee were calculated).

In 1980, nine industries accounted for 92.4 percent of the State's excess employment and 89.2 percent of the excess earnings--that is, its economic base (see tabulation below). The same industries accounted for a slightly larger share (93.8 percent) of excess employment and a slightly smaller share of excess earnings (85.2 percent) in 1970. In 1970, agriculture, for example, accounted for 31.6 percent of basic employment and 4.1 percent of basic earnings. The two percentages dropped to 24.6 and 3.9 percent, respectively. Manufacturing industries (textile, chemical, leather, forest and rubber products) on the other hand accounted for an increasingly larger share of the economic base. For employment, this share increased from 58.9 to 62 while it increased to an even larger percentage in earnings—70.4 to 74.6. The chemical and allied products industry was the largest gainer in market share among the manufacturers.

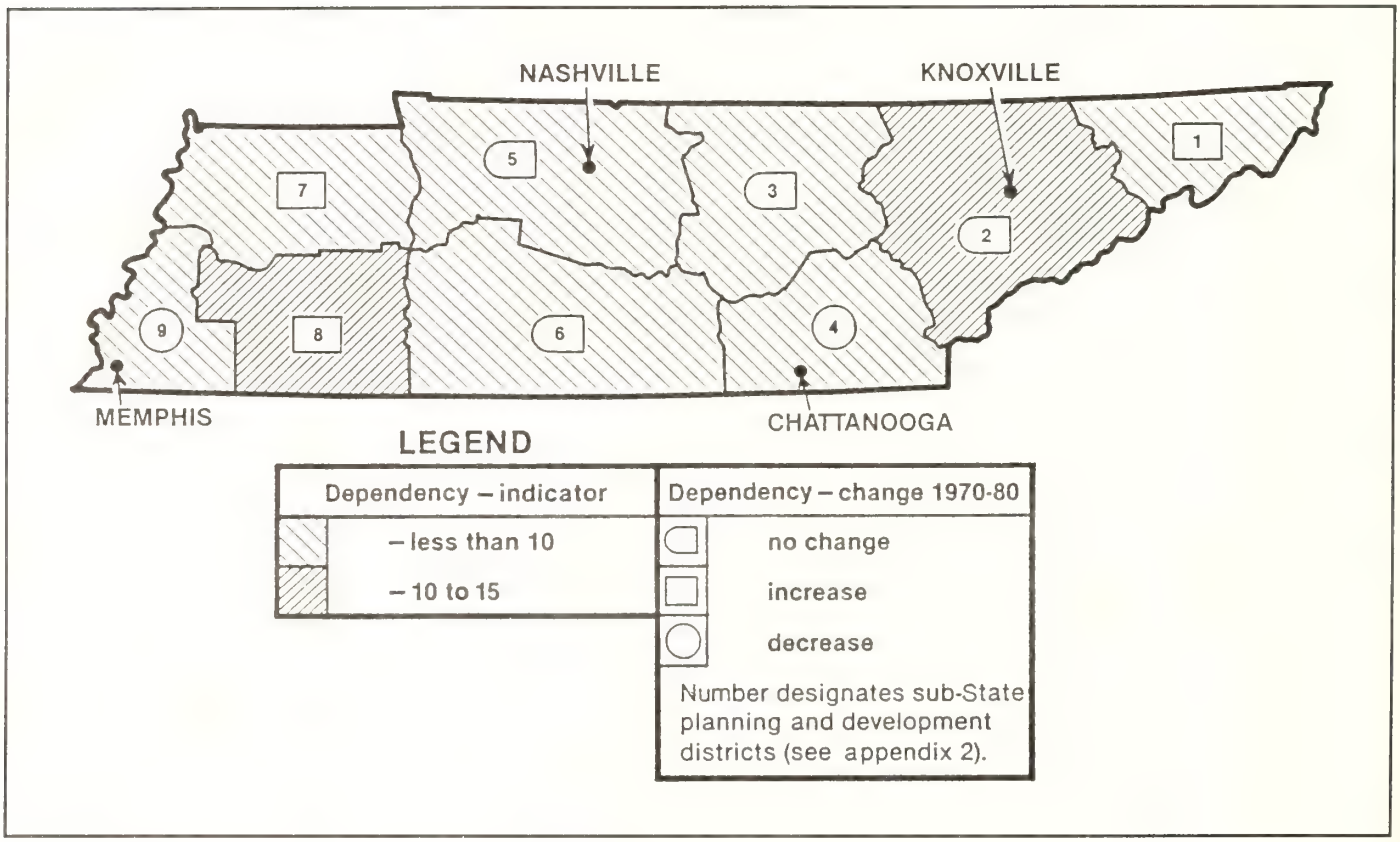
Federal civilian employment, which did not qualify as a basic industry in 1970, accounted for 6.2 percent of basic employment by the end of the decade. During the 1970's, the importance of the forest products industry increased slightly.

Both wholesale trade and trucking and warehousing qualify as basic industries. This phenomenon reflects Tennessee's role as a major regional trade and transportation center.

Economic base industries	Dependency indicator			
	1970		1980	
	EMP	EARN	EMP	EARN
	(Percent of economic base)			
Agriculture	31.6	4.1	24.6	3.9
Textile	24.8	20.0	22.4	15.2
Chemical and allied products	18.0	31.9	15.8	26.7
Federal civilian	—	—	6.2	14.2
Leather and leather products	7.2	7.2	6.1	5.0
Forest products industry	7.6	8.6	7.8	7.7
Rubber and miscellaneous products	1.3	2.7	3.7	5.6
Trucking and warehousing	1.7	4.2	3.6	7.4
Wholesale trade	1.6	6.5	2.2	3.5
Subtotal	93.8	85.2	92.4	89.2
All other basic industries	6.2	14.8	7.6	10.8
Total	100.0	100.0	100.0	100.0

Geographical Importance of the Forest Products Industry

The contribution of the forest products industry to Tennessee's economic base differed among sub-State districts (see appendix 2 for a list of counties by district). In district 6, the forest products industry accounted for only 1 percent of the economic base; in district 2, it accounted for 12 percent. Four districts—2, 4, 8, and 9—accounted for 75 percent of the basic employment in the State's forest products industry. A significant portion of this basic employment is associated with secondary processing in metropolitan areas.

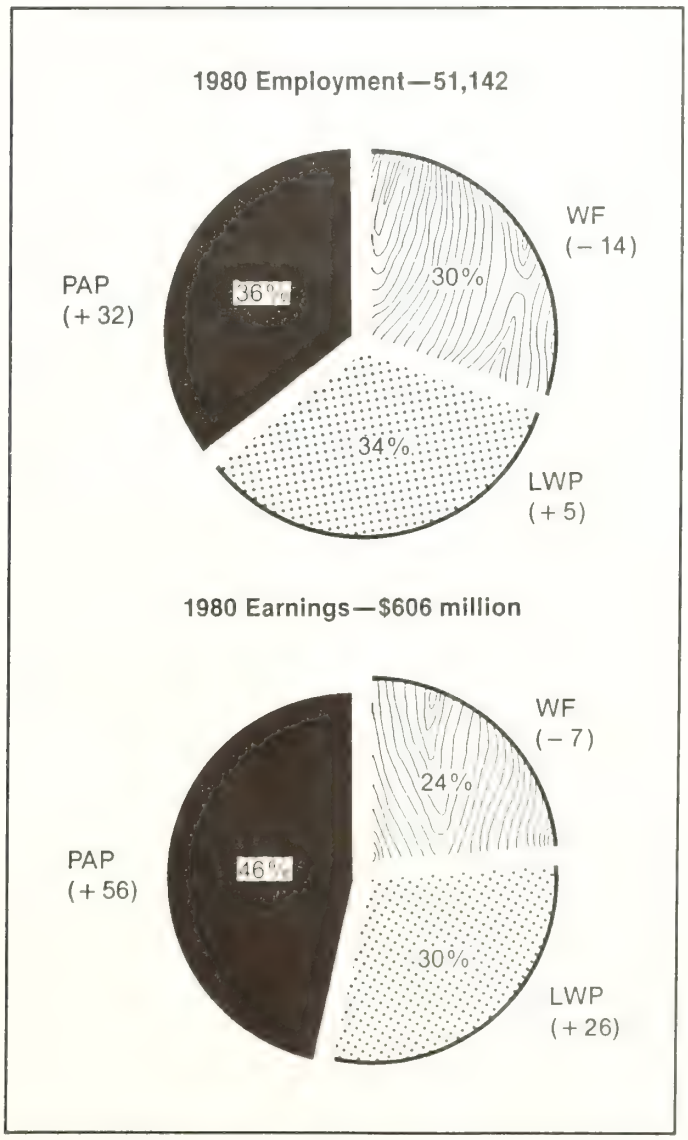


Source: Sub-State estimates for 1970 and 1980 were derived from unpublished county data series provided by the U.S. Department of Commerce, Regional Economic Information System, Washington, DC, and from the Department's *County Business Patterns*. The numbers designate sub-State districts corresponding to the geographical classification of counties as shown in appendix 2.

Composition of the Forest Products Industry

Tennessee's forest products industry is comprised of paper and allied products, lumber and wood products (not including mobile homes), and wood furniture manufacturing. Employment was almost equally distributed among the three segments in 1980, but paper and allied products accounted for nearly half of the total earnings in the State's forest products industry.

Although employment decreased in the wood furniture segment between 1970 and 1980, it increased in the other two segments. The growth in employment in the paper and allied products segment is particularly noteworthy. Earnings in wood furniture manufacturing, like employment, decreased between 1970 and 1980. Meanwhile, the other two segments experienced sizable increases in earnings.

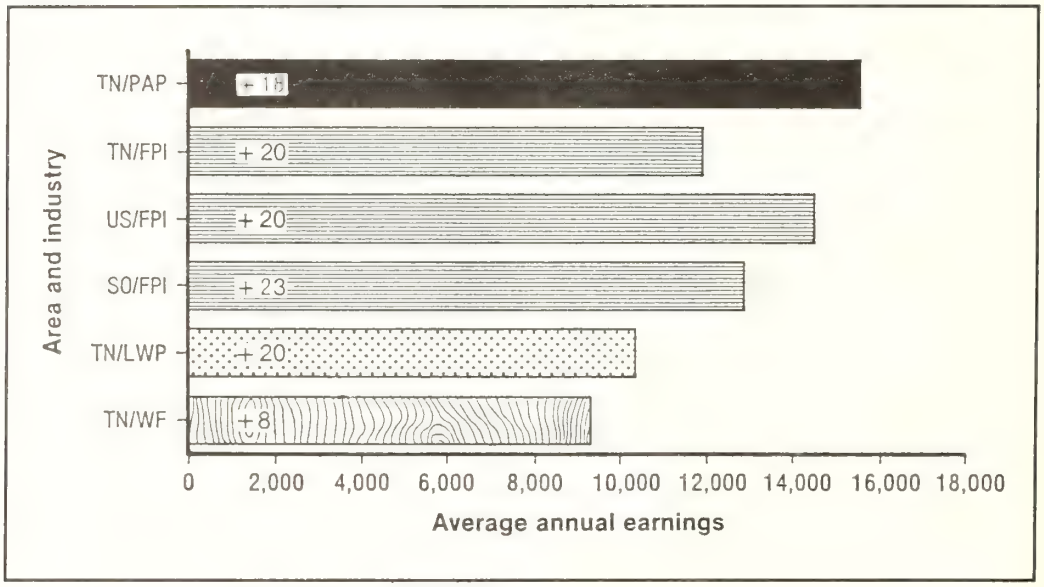


Numbers in parentheses show percentage of change from 1970 to 1980.

Average Annual Earnings per Worker

Average annual 1980 earnings per worker in paper and allied products were greater than were earnings in the other two segments of the forest products industry. Higher average skill levels, greater capital investment per worker, and unions account for this difference. At the State level, earnings in the wood furniture industry were about 60 percent of those for paper and allied products and were significantly below the average for all forest products industries in the South and the United States.

The rate of growth in average earnings was about the same for Tennessee's forest products industry as for the Nation but somewhat less than the average for the South. The rate of change for wood furniture was considerably less than that of the forest products industry in the Nation and the South.

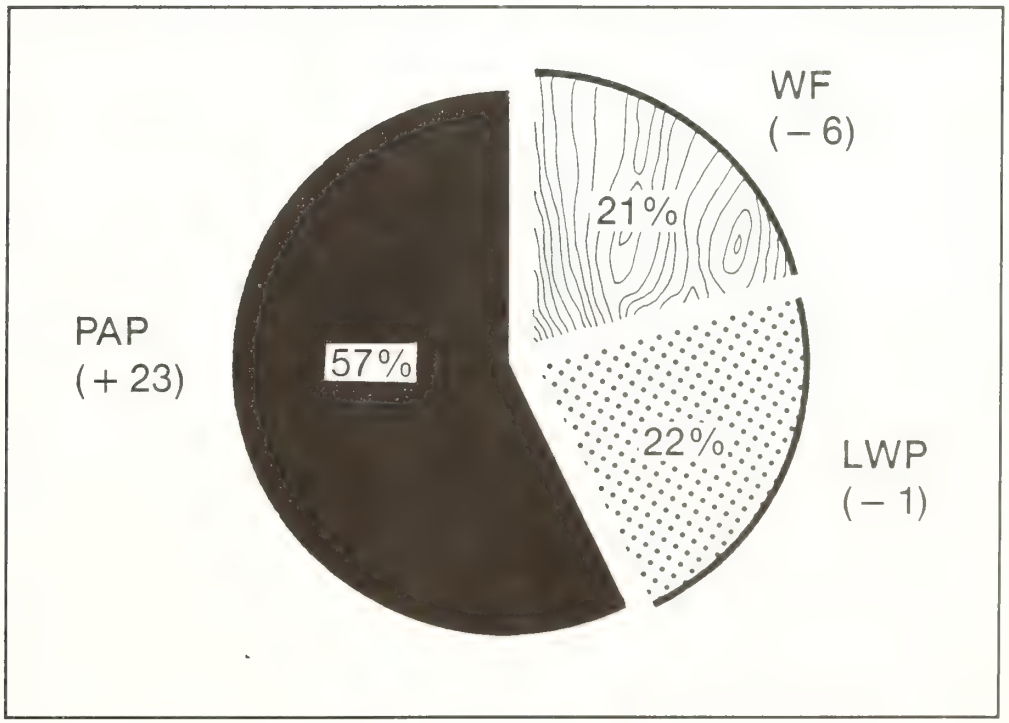


Numbers in bars show percentage of change from 1970 to 1980.

Value Added by the Forest Products Industry

Value added by manufacturing represents income payments made directly to workers and business owners; it is equal to the value of shipments less the cost of materials, parts, supplies, fuel, goods purchased for retail, electric energy, and contract work. Value of shipments includes goods and services provided by other industries. Value added includes only the economic contributions of the State's forest products industry. Consequently, value added by manufacturing is considered a better monetary gauge of the relative economic importance of a manufacturing industry. In 1977, paper and allied products had the largest share of the $1.1 billion of value added by Tennessee's forest products industry.

In addition to having above-average growth in employment, the forest products industry increased in value added between 1972 and 1977. The value added increased by 10 percent but only on the strength of paper and allied products; value added by the wood furniture and the lumber and wood products segments actually decreased.



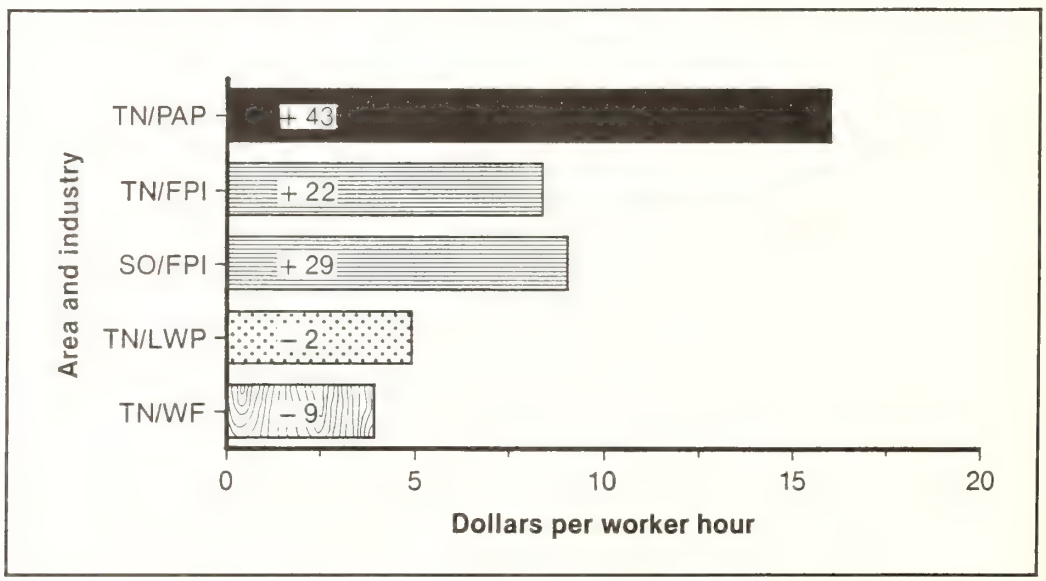
Numbers in parentheses show percentage of change from 1972 to 1977.

Capital Productivity

Increases in productivity are necessary for an industry to remain competitive. Productivity of an industry is measured in terms of value added minus payroll per worker hour—VAMP (see table 3 for an explanation of how productivity was calculated for Tennessee's forest products industry). This measure of productivity represents profits before taxes and adjusts for wide differences in payroll among industries.

Paper and allied products is more capital intensive than the other segments of the industry and in the past attracted considerable investment in new facilities and equipment. During the mid-1970's, its productivity consequently increased despite significantly higher and increasing labor costs. Furthermore, this segment exhibited a significantly larger gain in productivity than was average for the South.

Paper and allied products had, by far, the highest productivity in Tennessee's forest products industry. Productivity per worker hour was more than twice the average for the State's forest products industry. Productivity in the wood furniture and lumber and wood products segments, which was very low to begin with, decreased between 1972 and 1977.

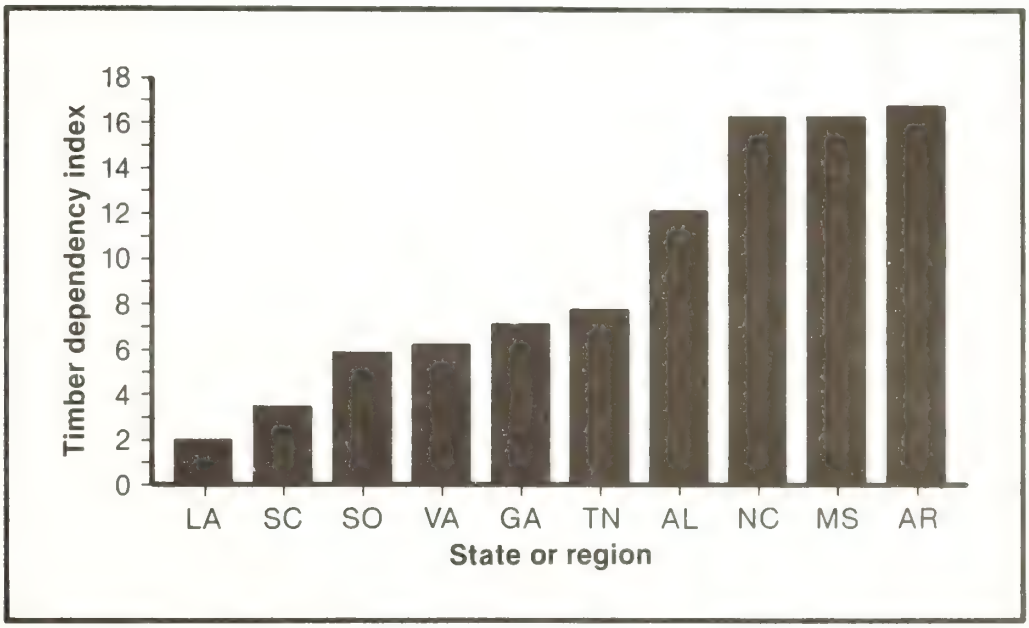


Numbers in bars show percentage of change from 1972 to 1977.

The Forest Products Industry in the South

Importance of the Industry Across the South

The dependency indicators suggest that in 1980 all but four States in the South manufactured forest products in excess of statewide needs. Florida, Kentucky, Oklahoma, and Texas were not self-sufficient in forest products; that is, these States imported more forest products than they exported. Consequently, on net balance, their respective forest products industries did not generate new dollars from the outside. In three States—Arkansas, Mississippi, and North Carolina—the forest products industry accounts for about one of six basic employees. Tennessee ranks fifth with about 1 of every 12 basic employees dependent on the forest products industry.



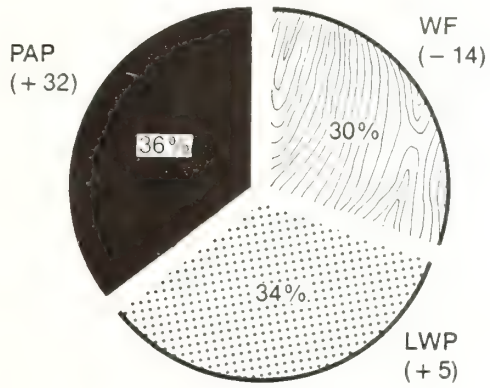
Industry Composition

Both the paper and allied products and the wood furniture segments accounted for larger shares of 1980 employment and earnings in Tennessee's forest products industry than they did for the South. During the 1970's, employment and earnings in the pulp and allied products segment increased at a much faster rate in Tennessee than in either the South or the Nation.

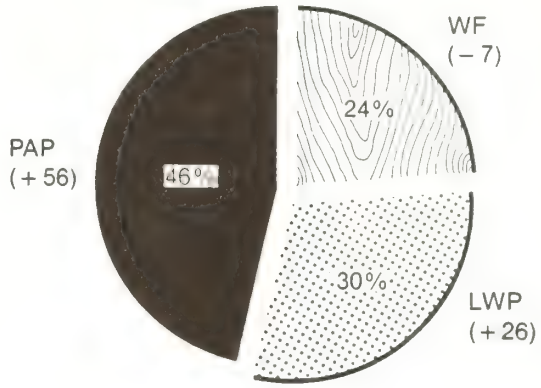
Wood furniture is more prominent in Tennessee than in the South and the Nation; but unlike the South and the Nation, earnings and employment in this segment declined in Tennessee.

TENNESSEE

1980 Employment—51,142

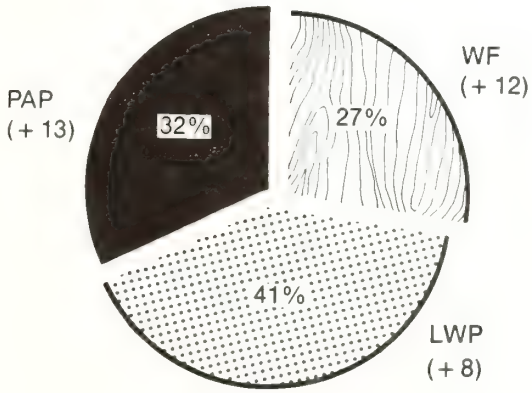


1980 Earnings—$606 million

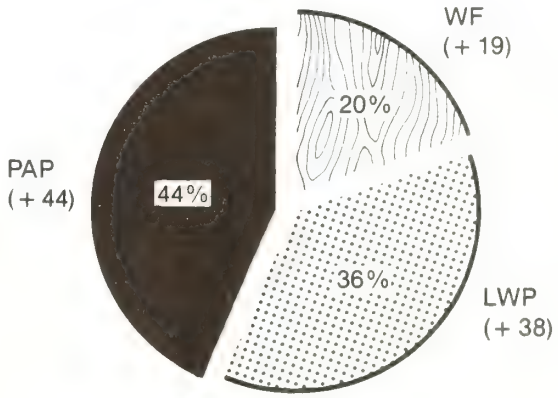


THE SOUTH

1980 Employment—620,567

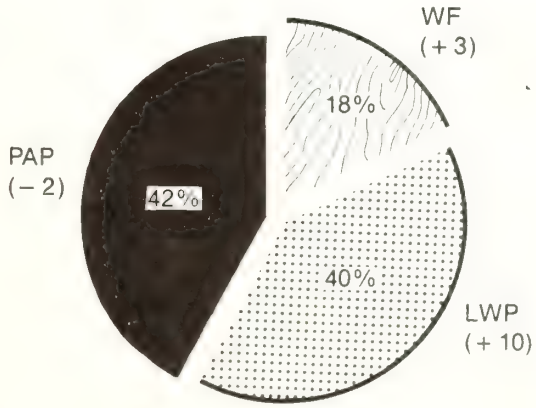


1980 Earnings—$7.96 billion

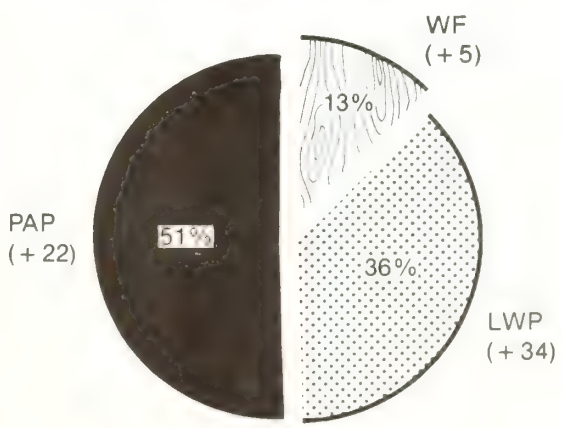


UNITED STATES

1980 Employment—1,634,000



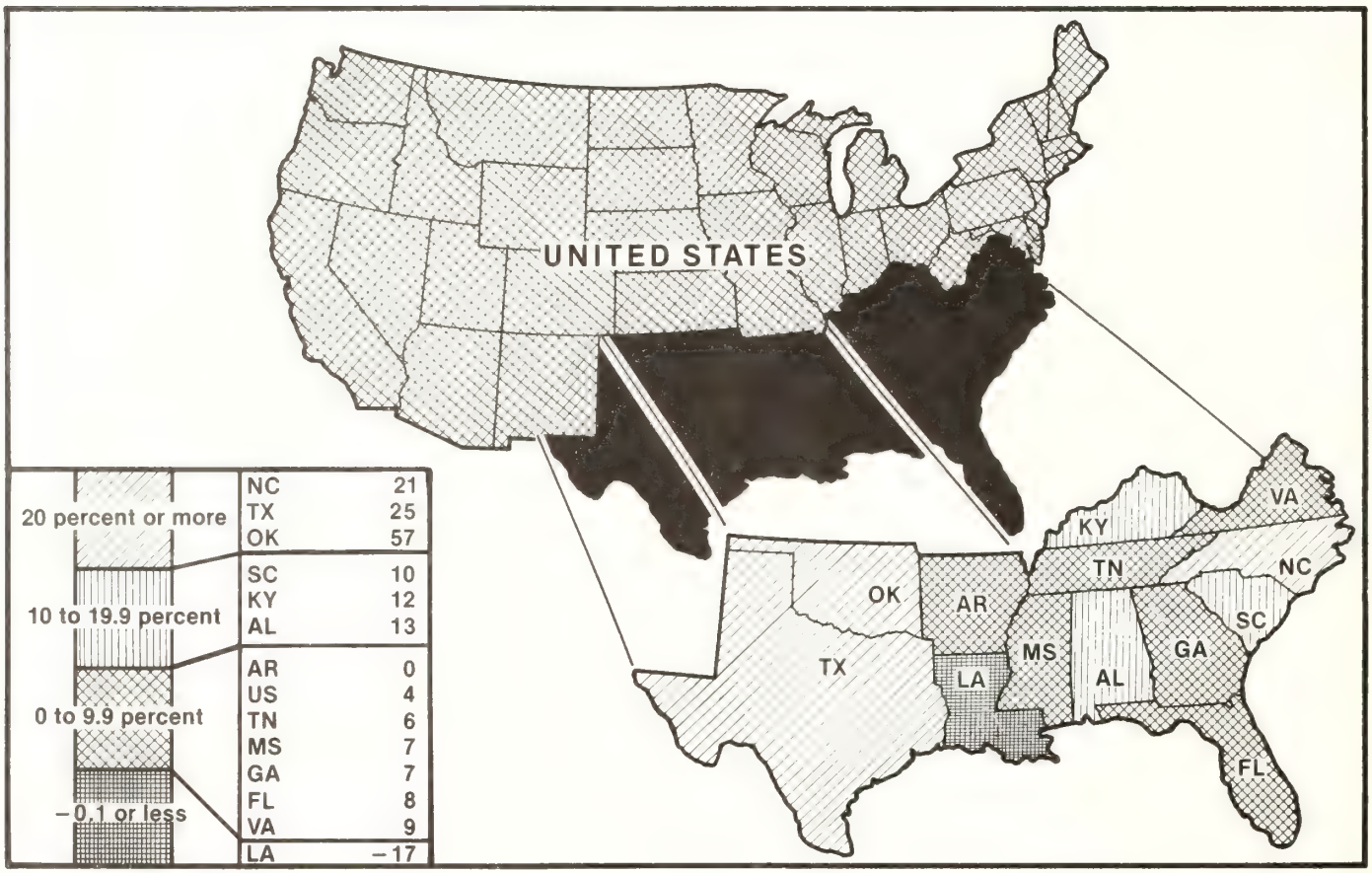
1980 Earnings—$23.65 billion



Numbers in parentheses show percentage of change from 1970 to 1980.

Growth of Employment

With the exceptions of Arkansas and Louisiana, employment in the forest products industry in each of the Southern States grew faster than did the U.S. counterpart. Between 1970 and 1980, employment in Oklahoma and Texas grew faster than the all-industry average of 22.3 percent. Between 1970 and 1980, employment in the forest products industry in Tennessee increased by more than 2,500.

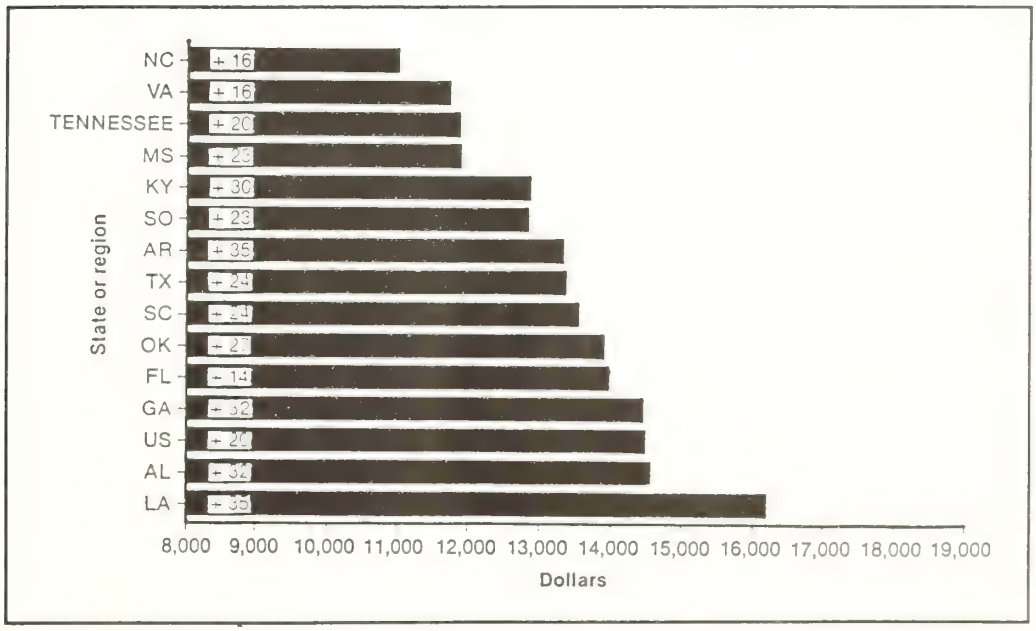


Average Annual Earnings

Average annual earnings per worker in the forest products industry differed significantly by State in 1980. About $5,000 separated the State with the highest (Louisiana) from the State with the lowest (North Carolina). Pulp and allied products manufacturing, which has traditionally paid higher wages than have other segments of the forest products industry, dominated Louisiana's forest products industry. Wood furniture, which has paid lower average wages, dominated North Carolina's industry.

Average annual earnings in the forest products industry in Tennessee were slightly below the average for all States in the South but significantly below the average for the United States. The increase in earnings was nearly the same for Tennessee, the South, and the Nation.

Generally speaking, paper and allied products dominated the forest products industry in the States with the highest average annual earnings. This relation reflects higher job skills and unions in pulp and paper manufacturing. Wages, by and large, were the lowest in States where the labor-intensive wood furniture industry was more important.



Numbers in bars show percentage of change from 1970 to 1980.

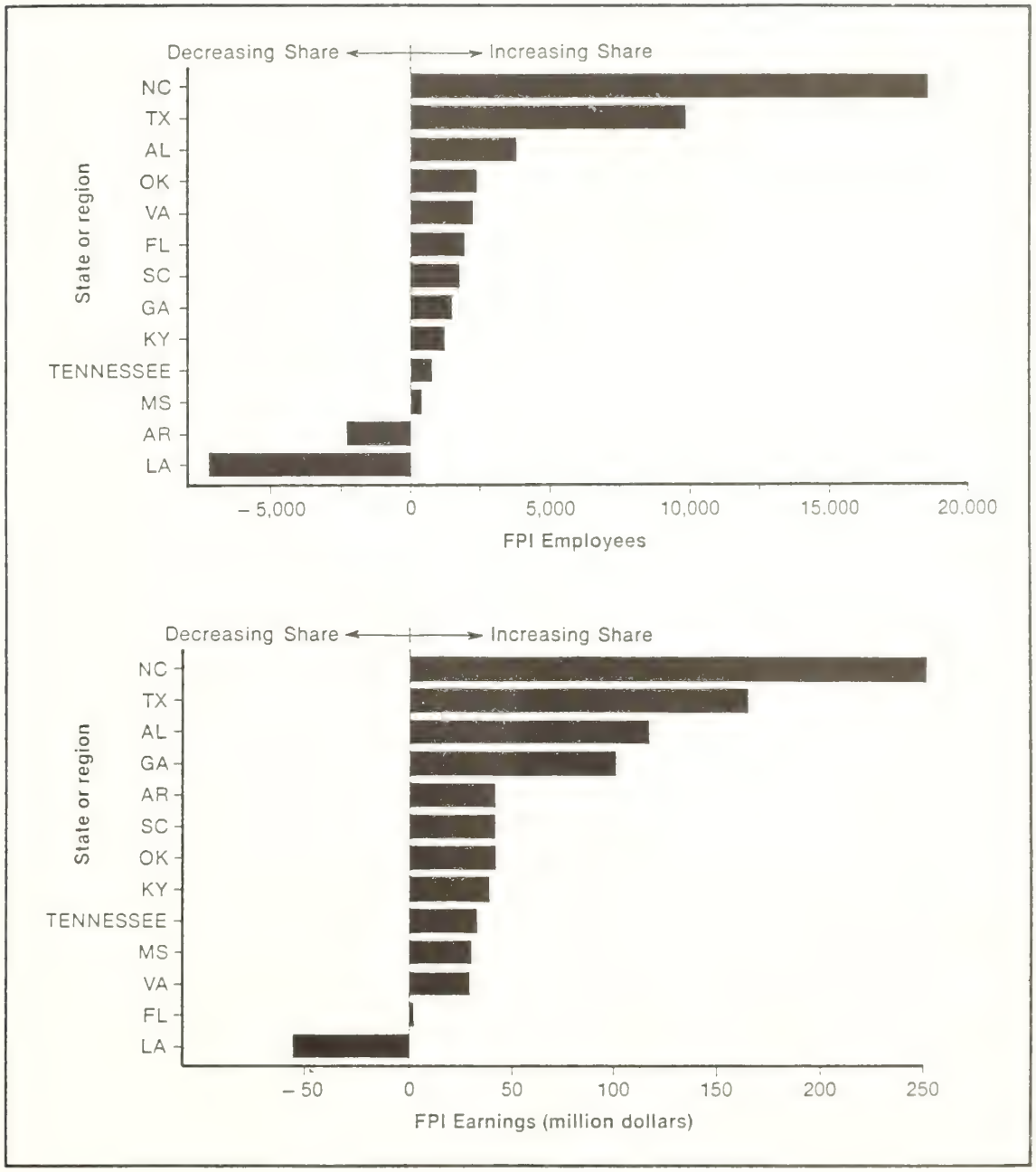
Shift in Employment and Earnings

Between 1970 and 1980, total employment in the Nation's forest products industry remained constant; with the exception of Louisiana, it increased in every Southern State. All Southern States except Arkansas and Louisiana increased their share of the Nation's forest products industry employment, and all but Louisiana increased their share of earnings.

The regional shift shows how much more or less employment and earnings a State would have had in the forest products industry in 1980 had it grown at the national rate. Tennessee, for example, had nearly 750 more employees in 1980 than it would have had if its forest products industry had grown at the national rate.

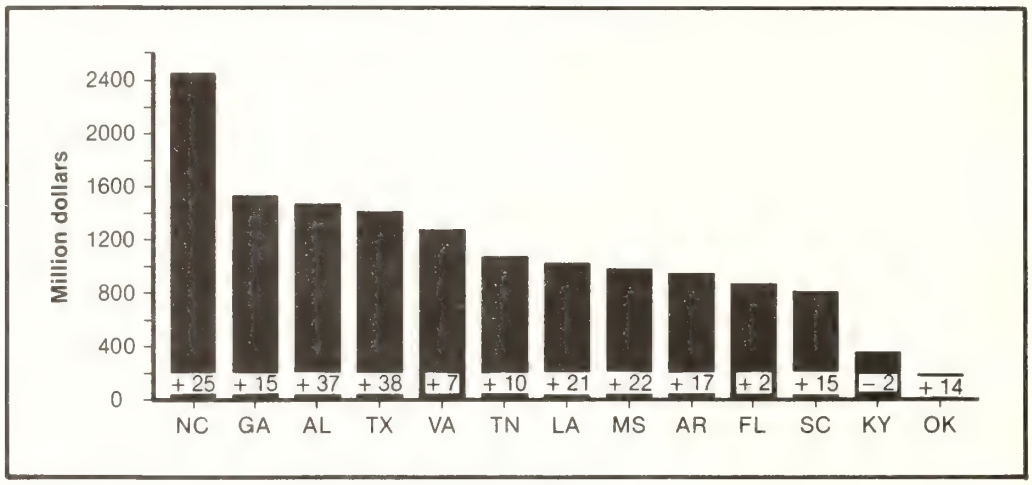
Increased shares of employment and earnings reflect the comparative advantage the South's forest products industry enjoyed over competitors elsewhere. Tennessee was one of the majority of Southern States in which the forest products industry improved its competitive position during the 1970's.

Several factors (for example, relatively lower labor costs, lower raw materials costs, and closer proximity to markets) might account for a State's comparative advantage, although adverse trends in one factor need not reduce a region's advantage. For instance, increasing labor costs need not adversely affect the South's comparative advantage if increased capital or labor productivity offsets higher labor costs.


Decreasing Share
Increasing Share
State or region
NC
TX
AL
OK
VA
FL
SC
GA
KY
TENNESSEE
MS
AR
LA
– 5,000
0
5,000
10,000
15,000
20,000
FPI Employees
Decreasing Share
Increasing Share
State or region
NC
TX
AL
GA
AR
SC
OK
KY
TENNESSEE
MS
VA
FL
LA
– 50
0
50
100
150
200
250
FPI Earnings (million dollars)

Value Added by the Forest Products Industry

In 1977, North Carolina led the South in value added by the forest products industry. Tennessee was sixth. Texas not only was one of the leading States in total value added but also led the South in the change in value added between 1972 and 1977. One State, Kentucky, produced less value added in 1977 than in 1972.



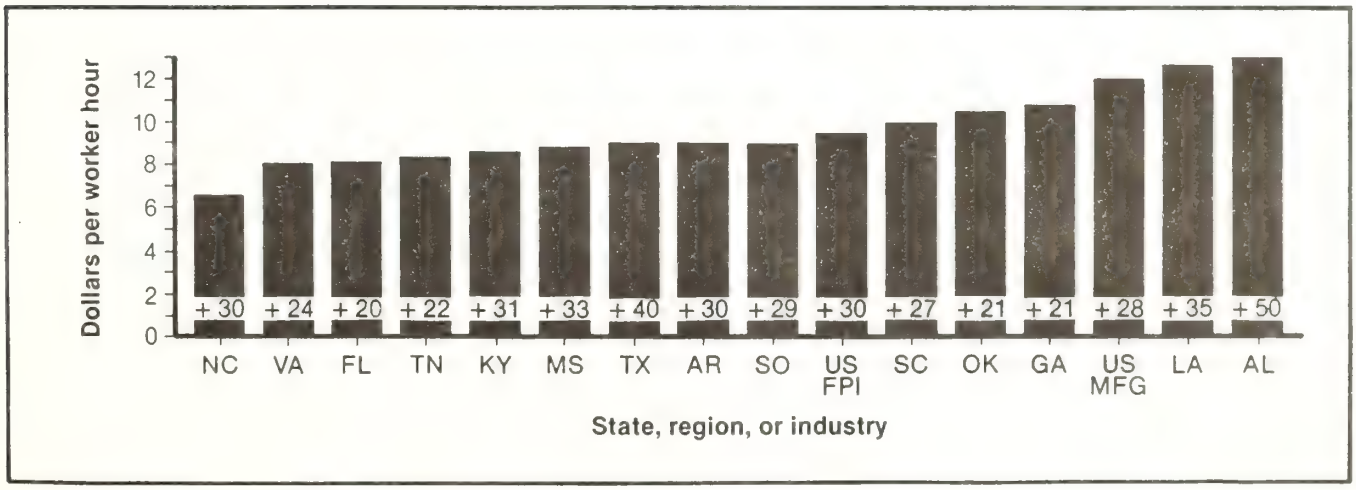
Numbers in bars show percentage of change from 1972 to 1977.

Capital Productivity

Paper and allied products, which is more capital-intensive and therefore more susceptible to technological change than are other segments of the forest products industry, exhibited the highest productivity within the forest products industry. Wood furniture, on the other hand, is the most labor-intensive of the three. North Carolina produced more value added than any other State in the South, but the productivity of its forest products industry in 1977 was the lowest, reflecting the dominant role of labor-intensive wood furniture manufacturing in North Carolina.

Increases in productivity exceeded increases in payroll per worker between 1972 and 1977 for all the Southern States. This relation is, in part, responsible for the South's comparative advantage in the forest products industry.

In Tennessee, growth of productivity in the paper and allied products segment (43 percent) far exceeded the average for the forest products industry and the average for all industries in the Nation in 1977. But the productivity of the other two segments declined. Productivity of Tennessee's forest products industry was therefore slightly below the average for the 13 Southern States. Growth in productivity of Tennessee's forest products industry exceeded that of only three of these States.



Numbers in bars show percentage of change from 1972 to 1977.

Acknowledgment

Many helpful suggestions of several reviewers were incorporated in this research report. This project was funded in part by USDA Forest Service, Resource Program and Assessment Staff, and State and Private Forestry, Area Planning and Development, State Planning for Forest Resources.

Appendix 1

Tables

Table 1–Total labor and proprietorial employment and income, by industry, Tennessee, 1980[1]

Industry number	Industry	Employees	Total income
		Number	*Thousand 1977 dollars*[2]
Wage and salary			
1	Agriculture	25,055	289,729
2	Agricultural services, forestry, and fisheries	6,881	56,794
3	Coal mining	4,184	98,929
4	Oil and gas extraction	686	11,696
5	Metal mining	1,607	27,225
6	Nonmetallic minerals	3,166	40,215
7	Construction	79,673	1,116,747
8	Food and kindred products	38,517	511,845
9	Tobacco	1,479	21,466
10	Textile mill production	26,269	249,988
11	Apparel and other textiles	69,089	481,495
12	Paper and allied products	18,197	281,845
13	Printing and publishing	23,930	273,865
14	Chemical and allied products	59,659	1,086,806
15	Petroleum refining	575	15,132
16	Rubber and miscellaneous plastics	23,295	324,067
17	Leather and leather products	19,262	169,946
18	Lumber and wood products excluding mobile homes	17,433	179,751
19	Mobile homes	1,155	11,919
20	Wood furniture	15,512	144,244
21	Other furniture and fixtures	5,725	53,236
22	Stone, clay, and glass products	14,695	221,914
23	Primary metals	17,929	338,946
24	Fabricated metals	32,965	444,623
25	Machinery, excluding electrical	35,582	508,198
26	Electrical machinery	40,191	475,469
27	Transportation equipment, excluding motor vehicles	10,034	165,586
28	Motor vehicles	11,964	186,981
29	Instruments and related equipment	5,904	70,833
30	Miscellaneous manufacturing	11,215	114,713
31	Railroad transportation	10,970	212,427
32	Trucking and warehousing	34,032	576,783
33	Local transit	4,029	50,779
34	Air transportation	7,889	154,607

See footnotes at end of table.

Table 1–Total labor and proprietorial employment and income, by industry, Tennessee, 1980[1] (continued)

Industry number	Industry	Employees	Total income
		Number	*Thousand 1977 dollars*[2]
Wage and salary			
35	Pipeline transportation	45	1,009
36	Transportation services	1,658	31,963
37	Water transportation	1,335	16,746
38	Communications	23,352	402,723
39	Electrical, gas, and sanitation services	4,201	78,143
40	Wholesale trade	110,495	1,555,598
41	Retail trade	268,218	2,071,328
42	Banking	26,187	28,3476
43	Other credit agencies	13,783	217,852
44	Insurance	27,672	420,202
45	Real estate and combinations	13,213	163,271
46	Hotel and other lodging	22,795	162,801
47	Personal, miscellaneous business, and repair services	66,065	683,392
48	Auto repair service	9,466	120,577
49	Amusement	11,206	87,954
50	Motion pictures	2,523	16,806
51	Private households	46,061	116,507
52	Medical and other health	90,360	1,257,103
53	Private education	25,807	227,591
54	Nonprofit organizations	41,804	257,667
55	Miscellaneous services	17,555	456,647
56	Federal civilian	74,204	1,181,170
57	Federal military	33,364	167,219
58	State and local government	268,727	2,315,093
Proprietorial			
59	Nonfarm proprietors	144,542	1,456,318
60	Farm Proprietors	112,792	193,796
	Total	2,210,120	22,833,608

1 Source of data for this table for Tennessee, other States of the South, and the United States: unpublished data, U.S. Department of Commerce, Regional Economics Measurements Division, Regional Economic Information System (REIS), Washington, DC, 1982. Unpublished data used by the U.S. Department of Commerce in preparing their *County Business Patterns* (CBP) series on employment and payroll were used to differentiate wood-related from nonwood-related employment and earnings. For example, CBP data were used to separate mobile homes (no. 19, above) from the lumber and wood products (no. 18) industry. Wood furniture (no. 20) was similarly separated from other furniture and fixtures (no. 21).

2 The Personal Consumption Expenditures (PCE) deflator, 1977 = 100, was used to deflate nominal dollars.

Table 2—Calculation of the 1980 dependency indexes for Tennessee

(In percent)

Industry	Employment		Tennessee excess employment[1]	Dependency index[2]
	Tennessee	United States		
Agriculture	1.38	1.46	—	—
Agricultural services, forestry, and fisheries	.38	.62	—	—
Farm proprietors	6.19	3.03	3.16	24.28
Coal mining	.23	.27	—	—
Oil and gas extraction	.04	.60	—	—
Metal mining	.09	.11	—	—
Nonmetallic minerals	.17	.14	.04	.29
Construction	4.37	4.74	—	—
Food and kindred products	2.11	1.87	.25	1.89
Tobacco	.08	.07	.01	.05
Textile mill production	1.44	.93	.51	3.93
Apparel and other textiles	3.79	1.39	2.41	18.48
Paper and allied products	1.00	.76	.24	1.84
Printing and publishing	1.31	1.37	—	—
Chemical and allied products	3.28	1.22	2.06	15.79
Petroleum refining	.03	.22	—	—
Rubber and miscellaneous plastics	1.28	.80	.48	3.71
Leather and leather products	1.06	.26	.80	6.13
Lumber and wood products, excluding mobile homes	.96	.71	.25	1.90
Mobile homes	.06	.05	.01	—
Wood furniture	.85	.32	.53	4.06
Other furniture and fixtures	.31	.19	.13	.97
Stone, clay, and glass products	.81	.73	.08	.59
Primary metals	.98	1.26	—	—
Fabricated metals	1.81	1.77	.04	.28
Machinery, excluding electrical	1.95	2.73	—	—
Electrical machinery	2.21	2.31	—	—
Transportation equipment, excluding motor vehicles	.55	1.21	—	—
Motor vehicles	.66	.87	—	—
Instruments and related equipment	.32	.77	—	—
Miscellaneous manufacturing	.62	.47	.15	1.15
Railroad transportation	.60	.58	.02	.14
Trucking and warehousing	1.87	1.40	.47	3.59
Local transit	.22	.29	—	—
Air transportation	.43	.50	—	—
Pipeline transportation	—	.02	—	—
Transportation services	.09	.22	—	—
Water transportation	.07	.23	—	—
Communications	1.28	1.48	—	—
Electrical, gas, and sanitation services	.23	.90	—	—
Wholesale trade	6.07	5.79	.28	2.15
Retail trade	14.73	16.50	—	—
Banking	1.44	1.72	—	—
Other credit agencies	.76	.99	—	—

See footnotes at end of table.

Table 2—Calculation of the 1980 dependency indexes for Tennessee (continued)

(In percent)

Industry	Employment		Tennessee excess employment[1]	Dependency index[2]
	Tennessee	United States		
Insurance	1.52	1.89	—	—
Real estate and combinations	.73	1.16	—	—
Hotel and other lodging	1.25	1.20	.05	.40
Personal, miscellaneous business, and repair services	3.63	4.69	—	—
Auto repair service	.52	.63	—	—
Amusement	.62	.84	—	—
Motion pictures	.14	.24	—	—
Medical and other health	4.96	5.71	—	—
Private education	1.42	1.47	—	—
Nonprofit organizations	2.30	3.01	—	—
Miscellaneous services	.96	1.63	—	—
Federal civilian	4.07	3.27	.80	6.17
Federal military	1.83	2.68	—	—
Nonfarm proprietors	7.94	7.66	.27	2.10
Total[3]	100.00	100.00	13.04	100.00

[1] Tennessee employment minus U.S. employment. Figures may not be exactly equal to Tennessee minus U.S. because of rounding. Dashes signify no excess employment.

[2] Individual industry excess employment expressed as a percentage of Tennessee's total excess employment (sum of column 4).

[3] Sum of parts may not equal totals because of rounding.

Table 3 —Value added, hours worked, payroll, and capital productivity,[1] Tennessee forest products industry, 1977 [2]

Industry	Value added	Payroll	Hours worked	Productivity	Productivity change, 1972-77
	- - $Million - -		*Million*	*$VAMP per hour*	*Percent*
Lumber and wood products	24.5	12.3	24.5	4.91	-1.57
Wood furniture	223.2	124.3	25.3	3.91	-9.08
Paper and allied products	618.4	211.8	25.5	15.95	+43.39

[1] Productivity equals value added minus payroll (VAMP) divided by hours worked. For a discussion of VAMP, see W. Charles Sawyer and Joseph A. Ziegler. 1980. "The use of VAMP shift as a predictive model." Unpublished paper presented at the annual meeting of the Western Regional Science Association, Monterey, California.

[2] Source: U.S. Bureau of the Census, Census of Manufactures, for 1972 and 1977, Tennessee and the United States, available in 1976 and 1980, respectively. In the few instances where data were not available for some subindustry segments, the distribution of the number of establishments was used to estimate nondisclosures.

Appendix 2

Tennessee Counties by Sub-State Planning and Development Districts

District code	Counties
1	Carter, Greene, Hancock, Hawkins, Johnson, Sullivan, Unicoi, Washington
2	Anderson, Blount, Campbell, Claiborne, Cocke, Grainger, Hamblen, Jefferson, Knox, Loudon, Monroe, Morgan, Roane, Scott, Sevier, Union
3	Cannon, Clay, Cumberland, DeKalb, Fentress, Jackson, Macon, Overton, Pickett, Putnam, Smith, Van Buren, Warren, White
4	Bledsoe, Bradley, Grundy, Hamilton, Marion, McMinn, Meigs, Polk, Rhea, Sequatchie
5	Cheatham, Davidson, Dickson, Houston, Humphreys, Montgomery, Robertson, Rutherford, Stewart, Sumner, Trousdale, Williamson, Wilson
6	Bedford, Coffee, Franklin, Giles, Hickman, Lawrence, Lewis, Lincoln, Marshall, Maury, Moore, Perry, Wayne
7	Benton, Carroll, Crockett, Dyer, Gibson, Henry, Lake, Obion, Weakley
8	Chester, Decatur, Hardeman, Hardin, Haywood, Henderson, Madison, McNairy
9	Fayette, Lauderdale, Shelby, Tipton

Maki, Wilbur R.; Schallau, Con H; Foster, Bennett B.; Redmond, Clair H. 1987. Tennessee's forest products industry: performance and contribution to the State's economy, 1970 to1980. Res. Pap. PNW-RP-386. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 22 p.

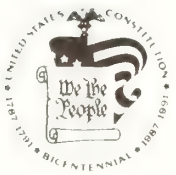
The forest products industry is one of Tennessee's basic industries; in 1980, for example, it accounted for about 1 of every 12 basic jobs. Furthermore, Tennessee was one of the majority of Southern States in which the forest products industry improved its competitive position during the 1970's. In 1977, productivity growth of the paper and allied products segment far exceeded the average for the forest products industry as well as the average for all industries.

Keywords: Forest products industries, economics (forest products industries), employment (forest products industries), Tennessee.

The **Forest Service** of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing Nation.

The U.S. Department of Agriculture is an Equal Opportunity Employer. Applicants for all Department programs will be given equal consideration without regard to age, race, color, sex, religion, or national origin.

Pacific Northwest Research Station
319 S.W. Pine St.
P.O. Box 3890
Portland, Oregon 97208



September 1987

U.S. Department of Agriculture
Pacific Northwest Research Station
319 S.W. Pine Street
P.O. Box 3890
Portland, Oregon 97208

BULK RATE
POSTAGE +
FEES PAID
USDA-FS
PERMIT No. G-40

Official Business
Penalty for Private Use, $300

do NOT detach label

United States
Department of
Agriculture

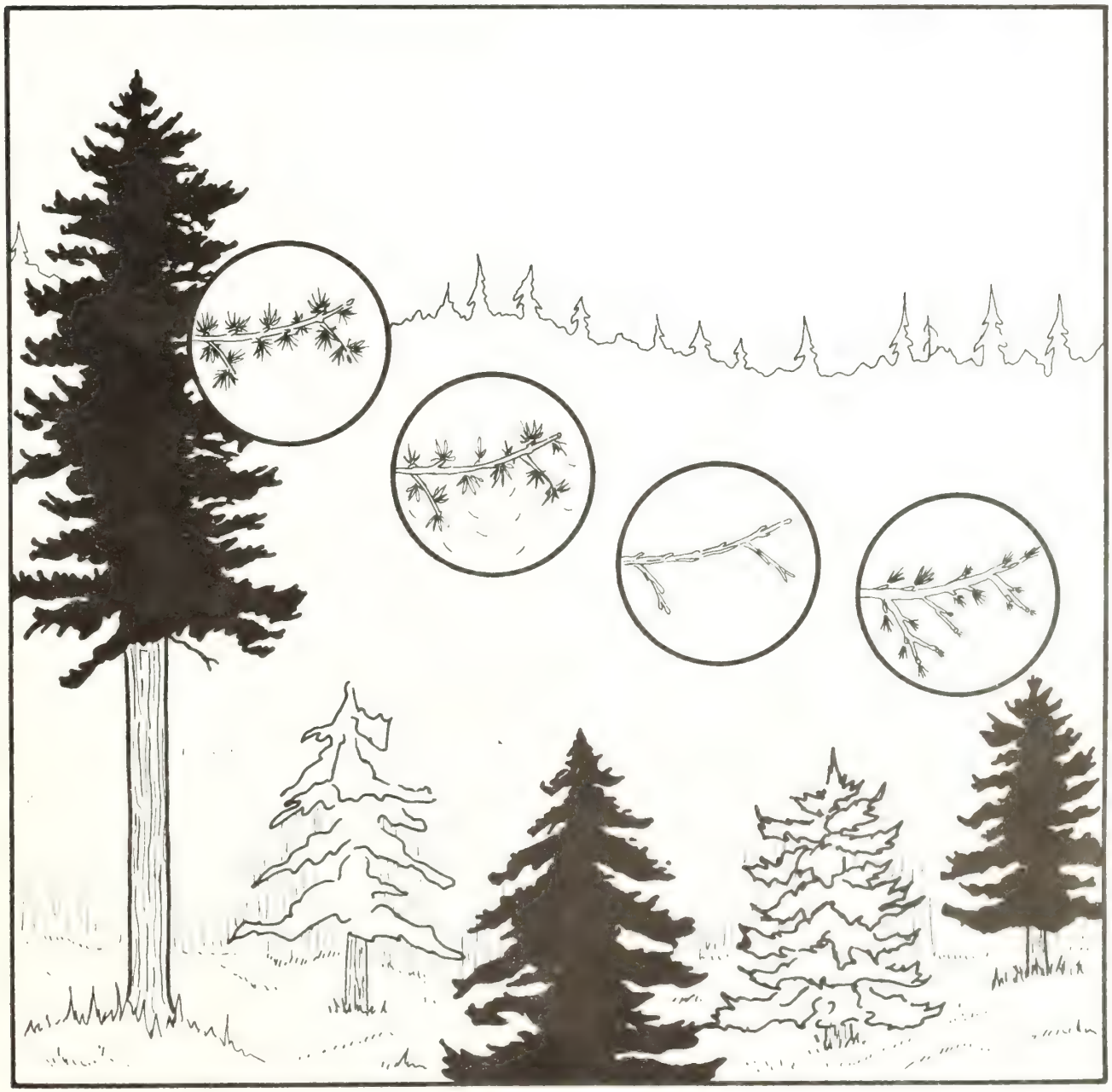
Forest Service

Pacific Northwest
Research Station

Research Paper
PNW-RP-387

Results After 20 Years From a Western Larch Levels-of-Growing-Stock Study

K.W. Seidel



Author

K.W. SEIDEL is a research forester at the Silviculture Laboratory, 1027 N.W. Trenton Avenue, Bend, Oregon 97701.

Abstract

Seidel, K.W. 1987. Results after 20 years from a western larch levels-of-growing-stock study. Res. Pap. PNW-RP-387. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 18 p.

The 20-year growth response from a levels-of-growing-stock study in an even-aged western larch stand in eastern Oregon, first thinned at age 33, showed that trees growing at low stand densities grew more rapidly in diameter than trees in high-density plots. Height growth was relatively uniform among density levels. Both basal-area and total cubic-volume increment increased as stand density increased. Despite the large reduction in volume increment at the low densities, most of the wood is concentrated on a few, fast-growing trees that can reach usable size sooner than slow-growing trees in high-density plots.

Keywords: Increment (stand volume), even-aged stands, stand density, thinning effects, growing stock (-increment/yield, western larch, *Larix occidentalis*.

Summary

A levels-of-growing-stock study was installed in a 33-year-old even-aged western larch stand in 1966 to provide basic growth and yield information for a wide range of stocking levels. The study is in eastern Oregon in a seral larch stand typical of the *Abies grandis/Calamagrostis rubescens* plant community. Ten plots were precommercially thinned from below to five density levels expressed as thousands of square feet of bole area per acre.

Stand density significantly affected diameter growth, which increased as growing-stock level decreased. During the 20 years after thinning, growth increased average stand diameter by 6.1 inches in low-density plots compared with 2.0 inches in high-density plots. Height growth was relatively uniform among density levels, and mortality was negligible, except in 1984 when an ice storm caused a loss of about 4 percent of the study trees at the two highest densities. Both basal-area and total cubic-volume increment increased significantly as stand density increased. Although total cubic-volume growth was greatest in high-density plots, wood was added more rapidly to fewer potentially usable trees in the low-density plots. Board-foot growth was greatest in the low-density plots because of the large amount of ingrowth from trees reaching merchantable size.

Evidence from another study (Schmidt 1966) suggests that the ideal time to precommercially thin overstocked larch stands is at 10 to 15 years of age, before crowns begin to shorten and diameter and height growth slows. As demonstrated in this study, however, considerable gains are possible from precommercial thinnings in larch stands up to 30 years of age and 45 feet tall. The proper intensity of thinning depends not only on timber management objectives but also on the importance of other forest resources to the land manager. For timber management, the primary factor influencing the residual stocking level is the manager's estimate of the minimum-size tree (diameter at breast height) that will be merchantable in the future. The larger the trees must be to support a commercial thinning, the fewer the trees that should remain after precommercial thinning; conversely, if smaller trees are merchantable, the residual stocking level should be higher. After stands reach merchantable size, density should be regulated by using the stocking-level curves prepared by Cochran (1985).

Contents

1 **Introduction**

1 **Study Area and Methods**

4 **Results and Discussion**

4 Diameter Growth

7 Height Growth

9 Mortality

10 Basal-Area Growth

11 Volume Growth

14 Total Yield and Tree Size

16 **Management Implications**

17 **Conclusions**

17 **Metric Conversions**

18 **Literature Cited**

Introduction

Western larch (*Larix occidentalis* Nutt.) is an important seral species in the Blue Mountains of northeastern Oregon because of its rapid juvenile growth and desirable wood properties. Even-aged larch stands generally become established after fire or other disturbance and are often heavily overstocked. Control of stand density by thinning is an essential part of managing young larch stands. Because larch is shade intolerant, tree crowns in unthinned stands are reduced in size as early as 9 years of age; the result is a loss of vigor and a decrease in diameter and height growth (Schmidt 1966).

Although some information is available on the response of larch crop trees to thinning in Montana and British Columbia (Cole 1984, Illingworth 1964, Roe and Schmidt 1965, Thompson 1969), long-term data on growth response of managed stands to various growing-stock levels is lacking. Levels-of-growing-stock and spacing studies provide information on long-term growth and yield for managed stands so forest managers can design thinning schedules to meet timber production and multiple-use objectives. This information is also needed to construct and verify simulation models for managed stands.

This paper reports 20-year growth-and-yield results from a levels-of-growing-stock study begun in 1966 in northeastern Oregon. The study was designed to provide basic information on the growth response of young, even-aged larch stands to a wide range of stocking levels. Results for the first three 5-year periods were reported by Seidel (1971, 1977, 1982).

Study Area and Methods

The study is in the La Grande Ranger District, Wallowa-Whitman National Forest, about 15 miles southeast of Union, Oregon, at an elevation of about 4,000 feet. The stand was 33 years old in 1966 and has a site index of about 80 feet at total age 50 years.[1]

All plots were well stocked before the initial thinning; each contained at least 25,000 square feet of bole area per acre (119 square feet of basal area) (table 1).[2] There were about 1,300 trees per acre, averaging 4.5 inches in diameter at breast height (d.b.h.) and 45 feet tall. All trees were larch except for one plot at the highest density and one plot at the second-highest density where about 40 percent of the bole area and basal area left after the initial thinning was lodgepole pine (*Pinus contorta* Dougl. ex Loud.).

The soil is a Tolo silt loam, a well-drained Regosol developed from dacite pumicite originating from the eruption of Mount Mazama (Crater Lake) about 6,500 years ago. It is underlain about 3 feet down by a buried soil developed from basalt.

Ground vegetation in the study area is typical of the *Abies grandis/Calamagrostis rubescens* plant community (Franklin and Dyrness 1973). Genera of shrubs and herbs such as *Arnica, Hieracium*, and *Ribes* are common.

---

[1] Site index of plots is based on curves in Schmidt and others (1976). These curves use total age (age at ground line).

[2] Bole area is a close approximation of the cambial area of the main stem. See Lexen (1943) and Smith (1962, p. 102) for discussions of the advantages of bole area as a measure of stand density.

Table 1—Stand characteristics per acre of western larch before and after the 1966, 1976, and 1986 thinnings and in 1971 and 1981

Level[a]	Density: Bole area	Density: Basal area	Number of trees	Average spacing	Quadratic mean diameter	Average height[b]	Volume[c]: Total	Volume[c]: Merchantable (including ingrowth)	Volume[c]: Board feet
	Square feet			*Feet*	*Inches*	*Feet*	*Cubic feet*		
				BEFORE INITIAL (1966) THINNING (AGE 33)					
1	25,800	118.6	924	6.9	4.9	48.4	1,995	1,180	48
2	31,125	132.7	1,161	6.1	4.6	46.2	2,287	1,088	0
3	34,180	139.2	1,406	5.6	4.3	46.5	2,367	855	193
4	32,880	143.7	1,377	5.6	4.4	42.9	2,322	1,125	0
5	32,700	135.6	1,459	5.5	4.1	42.0	2,200	964	0
Average	31,337	134.0	1,265	5.9	4.4	45.2	2,234	1,048	48
				AFTER 1966 THINNING (AGE 33)					
1	4,708	26.0	96	21.3	7.0	48.4	474	389	48
2	9,524	49.6	215	14.2	6.5	46.2	902	648	0
3	14,242	70.9	355	11.2	6.1	46.5	1,272	782	193
4	19,313	96.4	546	8.9	5.7	42.9	1,616	1,039	0
5	24,203	109.8	745	7.6	5.2	42.0	1,847	961	0
				1971 (AGE 38)					
1	6,374	40.3	96	21.3	8.8	55.4	794	678	948
2	12,069	68.2	215	14.2	7.6	51.7	1,333	1,060	294
3	17,797	93.4	354	11.1	7.0	53.3	1,780	1,261	532
4	23,810	120.5	539	9.0	6.4	49.1	2,250	1,562	345
5	29,121	134.3	740	7.7	5.8	48.0	2,510	1,435	102
				BEFORE 1976 THINNING (AGE 43)					
1	8,730	56.3	96	21.3	10.4	62.7	1,222	1,164	3,654
2	15,207	86.1	215	14.2	8.6	56.6	1,870	1,716	2,366
3	21,716	114.8	354	11.1	7.7	58.2	2,471	2,173	1,464
4	29,244	143.9	534	9.0	7.0	55.5	3,103	2,584	1,168
5	33,917	155.7	734	7.7	6.2	53.6	3,317	2,445	706
				AFTER 1976 THINNING (AGE 43)					
1	5,078	34.2	51	29.2	11.1	64.9	760	731	2,876
2	10,006	59.3	129	18.4	9.2	62.8	1,301	1,216	2,368
3	15,012	82.7	225	13.9	8.2	62.7	1,808	1,627	1,464
4	20,029	104.0	333	11.4	7.6	60.9	2,248	1,957	1,168
5	24,779	121.0	464	9.7	6.9	61.7	2,621	2,138	706
				1981 (AGE 48)					
1	6,592	44.6	51	29.2	12.6	72.8	1,146	1,116	5,110
2	12,505	72.9	129	18.5	10.3	68.9	1,862	1,770	4,949
3	18,737	99.3	224	13.9	9.0	67.8	2,412	2,264	3,583
4	24,433	121.2	329	11.6	8.3	66.4	2,986	2,740	2,797
5	29,960	137.6	462	9.8	7.4	66.0	3,398	2,959	1,357
				BEFORE 1986 THINNING (AGE 53)					
1	7,582	52.7	51	29.2	13.8	74.7	1,514	1,484	7,583
2	14,363	82.9	128	18.6	11.0	69.6	2,294	2,202	8,915
3	21,158	110.9	220	14.1	9.6	68.7	2,962	2,814	7,253
4	27,185	132.9	318	11.8	8.8	67.9	3,625	3,480	5,628
5	30,847	137.8	408	10.4	7.9	69.4	3,858	3,549	3,028
				AFTER 1986 THINNING (AGE 53)					
1	5,056	36.4	32	37.4	14.7	78.6	1,065	1,044	5,463
2	10,147	59.9	87	22.5	11.3	71.3	1,671	1,604	7,197
3	15,091	81.5	148	17.2	10.0	71.5	2,206	2,096	6,200
4	19,945	101.7	218	14.3	9.4	70.0	2,776	2,665	5,269
5	25,042	115.1	313	11.9	8.2	71.3	3,241	2,982	2,899

[a] Two plots for each density level.

[b] Average height of trees measured with dendrometer (about 15 trees per plot).

[c] Total cubic-foot volume—entire stem, inside bark, all trees; merchantable cubic-foot volume—trees 5.0-inch d.b.h. and larger to a 4-inch top diameter inside bark (d.i.b.); board-foot (International 1/4-inch rule) volume—trees 10.0-inch d.b.h. and larger to a 6-inch top d.i.b.

Figure 1—A plot after initial thinning in 1966 to an average spacing of 14 feet. Bole area is about 10,000 square feet per acre, and basal area is about 50 square feet per acre.

The experiment is a levels-of-growing-stock study designed for thinning at 10-year intervals. It consists of a completely randomized design with two replicates of five levels of growing stock installed on ten 0.4-acre plots (each surrounded by a 30-foot-wide buffer strip). The growing-stock levels selected for testing were 5,000, 10,000, 15,000, 20,000, and 25,000 square feet of bole area per acre. Actual stand densities after thinning in terms of bole area and basal area are given in table 1. The two plots assigned to each density level were thinned to about the same bole-area level in 1966, 1976, and 1986.

In general, plots were thinned from below to leave the required number of largest and most vigorous trees as evenly spaced as possible (fig. 1). None of the slash from the thinnings was removed from the plots.

Diameters of all plot trees were measured to the nearest 0.1 inch after the 1965, 1970, 1975, 1980, and 1985 growing seasons. On each plot, about 15 trees, proportionately distributed over the range of diameters, were measured with an optical dendrometer in 1966, 1970, 1975, 1980, and 1985. Some of the trees chosen in 1966 have been cut in subsequent thinnings and replaced with other trees. The measurements were used to develop an equation expressing volume and bole area of the entire stem inside bark as a function of diameter. New coefficients were calculated after each measurement and used to compute plot volumes (cubic feet and board feet, International 1/4-inch rule) at the beginning and end of the four 5-year periods (1966-70, 1971-75, 1976-80, and 1981-85). Height growth of trees chosen for volume-equation measurements was also measured by dendrometer.

Split-plot-in-time analyses of variance were used to test for significance of treatment effects. Tukey's test was used to determine significant differences among treatment means. Nonlinear regression analyses related diameter, basal area, and volume growth to residual bole area and basal area. The curvilinear model is the same one used in the earlier reports of this study:

$$Y = a + b\,(1 - e^{-cX})^{d};$$

where:

Y = diameter, basal area, or volume growth;

X = residual bole area or basal area;

e = natural base of logarithms = 2.71828....; and

a,b,c,d = regression coefficients.

Results and Discussion

Diameter Growth

Diameter growth consistently responded to changes in stand density during all four 5-year growth periods. Average growth was greatest on the most heavily thinned plots and decreased as stand density increased (table 2), partly because of more small, slow-growing trees in the high-density plots. The periodic annual diameter-growth rate at the lowest density was three to four times the growth at the highest density during the 20 years of the study. Differences in rates of diameter growth between the lowest density and all others were significant ($P<0.01$) for each 5-year period. Significant differences also were found between some other densities (2 vs. 4, 2 vs. 5, and 3 vs. 5).

Diameter growth was greatest during the first period at each density level, intermediate during the second and third, and slowest during the fourth (table 2). Growth in the first period was significantly greater ($P<0.01$) than in any of the later periods, and growth in the fourth period was significantly less than in any of the earlier periods. No significant differences in growth existed between the second and third periods. A significant interaction ($P<0.05$) was found between growth periods and density levels, probably because growth was greater during the second period at some levels; at other levels, growth was greater during the third period, although differences were small.

A significant ($P<0.01$) curvilinear relationship was found between periodic annual diameter increment and bole area or basal area at the beginning of each growth period (figs. 2 and 3). Bole area and basal area each accounted for about 98 percent of the variation in diameter growth between plots during the first three periods and for about 90 percent of the variation during the fourth period. The excellent correlation between diameter growth and stand density suggests that land managers can predict—with a reasonable degree of confidence—periodic annual diameter-growth rates after thinning 33- to 48-year-old larch stands of site index 80.

Table 2—Periodic annual increment and mortality per acre of western larch by age and density level after thinning at age 33 and 43

Density level	Residual density: Bole area	Residual density: Basal area	Diameter growth[a]	All trees: Basal area growth: Net	Basal area growth: Mortality	Basal area growth: Gross	Total volume growth: Net	Total volume growth: Mortality	Total volume growth: Gross	Merchantable volume growth (including ingrowth): Net	Merchantable volume growth (including ingrowth): Mortality	Merchantable volume growth (including ingrowth): Gross	Ingrowth: Board feet	Ingrowth: Percent	75 largest trees: Diameter growth[a]	75 largest trees: Gross total volume growth
	Square feet		*Inches*	*- - Square feet - -*			*- - Cubic feet - -*			*- - Board feet - -*			*Board feet*	*Percent*	*Inches*	*Cubic feet*
							AGE, 33-38 YEARS (1966-70)									
1	4,700	26.0	0.36	2.86	0	2.86	64	0	64	180	0	180	170	94.4	0.36	54
2	9,500	50.0	.23	3.72	0	3.72	86	0	86	59	0	59	59	100.0	.27	40
3	14,250	71.0	.18	4.50	.03	4.53	102	1	103	68	0	68	43	63.2	.24	31
4	19,300	96.0	.14	4.82	.19	5.01	127	4	131	69	0	69	69	100.0	.22	30
5	24,200	110.0	.11	4.90	.17	5.07	133	3	136	22	0	22	22	100.0	19	28
							AGE, 38-43 YEARS (1971-75)									
1	6,400	40.0	.32	3.20	0	3.20	85	0	85	541	0	541	403	74.5	33	73
2	12,100	68.0	.19	3.58	0	3.58	107	0	107	414	0	414	374	90.5	20	48
3	17,800	93.0	.15	4.28	0	4.28	138	0	138	186	0	186	130	70.2	.18	48
4	23,800	120.1	.12	4.69	.16	4.85	170	3	173	164	0	164	125	76.2	.16	44
5	29,100	134.0	.08	4.29	.11	4.40	161	2	163	120	0	120	96	80.0	.14	32
							AGE 43-48 YEARS (1976-80)									
1	5,078	34.0	.31	2.07	0	2.07	78	0	78	447	0	447	129	28.1	.31	78
2	10,006	59.0	.20	2.73	0	2.73	113	0	113	517	0	517	333	66.4	.22	79
3	15,012	83.0	.15	3.32	0	3.32	121	0	121	424	0	424	323	76.6	.18	55
4	20,029	104.0	.13	3.44	.05	3.49	147	1	148	326	0	326	227	73.1	.15	51
5	24,779	121.0	.10	3.32	.06	3.38	156	1	157	131	0	131	101	77.4	13	44
							AGE, 48-53 YEARS (1981-85)									
1	6,592	44.6	.22	1.62	0	1.62	74	0	74	495	0	495	0	0	22	74
2	12,505	72.9	.14	2.00	.07	2.07	86	2	88	793	0	793	426	54.5	.15	64
3	18,737	99.3	.12	2.32	.33	2.65	110	8	118	734	0	734	376	52.8	14	64
4	24,433	121.2	10	2.35	.66	3.01	128	16	144	566	0	566	361	66.8	.13	53
5	29,960	137.6	.07	0.04	2.37	2.41	92	56	148	335	0	335	212	61.3	.11	51

[a] Arithmetic diameter growth of trees living through four 5-year periods (1966-70, 1971-75, 1976-80, and 1981-85).

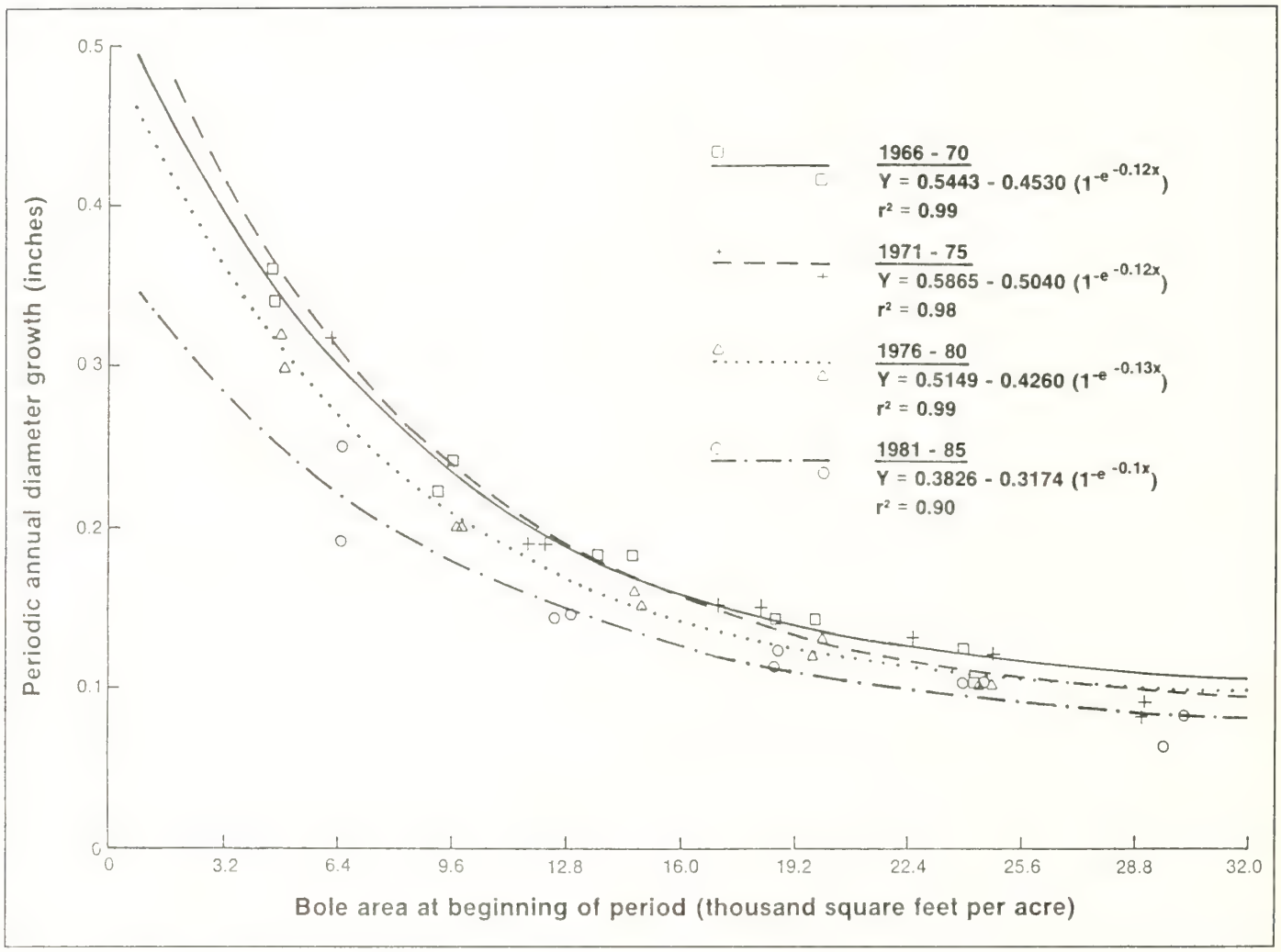


Figure 2—Periodic annual diameter growth by density level (bole area) and growth period.

The effect of the second thinning in 1976 was to prevent the normal decline in diameter growth associated with age and increased stand density, rather than to increase growth above that of the previous period. This result suggests that frequent thinnings (about every 5 years) are neccessary if a uniform rate of diameter growth is to be maintained. A uniform diameter-growth rate cannot be maintained indefinitely by repeated thinnings, but it appears to be attainable to at least a stand age of about 50 years.

During the 20 years of this study, the mean stand diameter increased by 9.8 inches in the lowest density plots and 4.1 inches in the highest density plots (table 3). About one-half of this increase was the result of removing the smallest trees during the three thinnings. Because of cutting the small, slow-growing trees and fast growth on the residual trees in the lowest density plots, the mean diameter in these plots was 79 percent greater in 1986 than in the highest density plots (14.7 vs. 8.2 inches) (table 1). Diameter growth of larch and lodgepole pine was similar during all four periods.

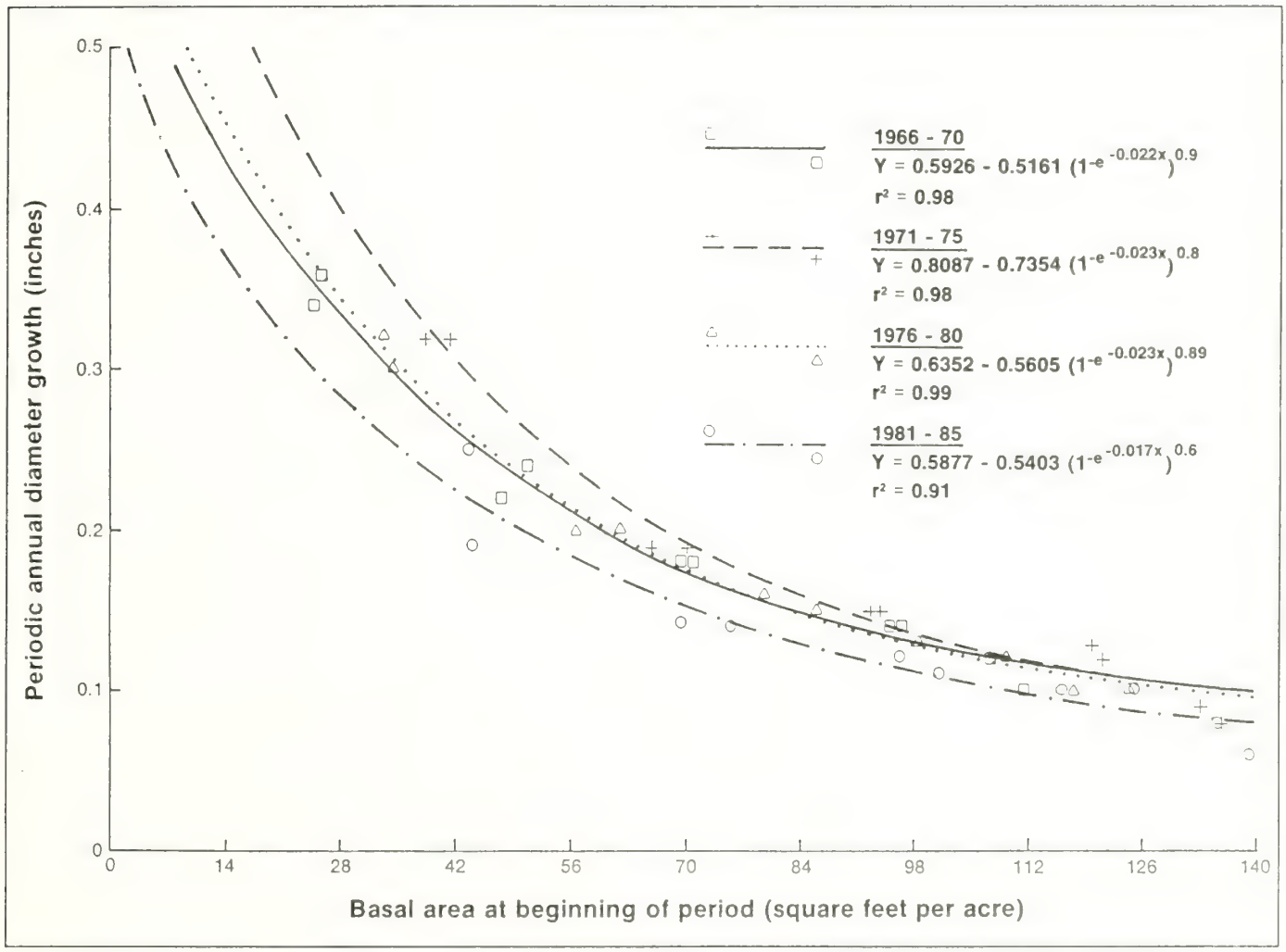


Figure 3—Periodic annual diameter growth by density level (basal area) and growth period.

Height Growth

Average annual height growth ranged from a low of 0.5-foot at the second-lowest density (fourth period) to a high of 1.6 feet at the lowest density (third period) (fig. 4). Height growth was relatively uniform among density levels, but a significant difference ($P<0.05$) in growth among levels occurred because of the slightly increased growth at the lowest level. Differences in height growth between periods also were significant ($P<0.05$); this was entirely the result of a pronounced decrease in growth during the fourth period. A severe ice storm in January 1984 did considerable damage to terminals so that average height growth was only about one-half that of the previous three periods. Height growth of larch and lodgepole pine was about the same during all periods.

Table 3—Increase in quadratic mean diameter of a western larch stand from 1966 to 1986 as a result of growth and 3 thinnings, by growth period and density level (bole area)

Bole-area level	Increase in quadratic mean diameter	Increase attributed to—		
		Thinning	Growth	Growth
Thousand square feet per acre	*Inches*			*Percent*
	1966-70 (AGE 33-38)			
5	3.9	2.1	1.8	46
10	3.0	1.9	1.1	37
15	2.7	1.8	.9	33
20	2.0	1.3	.7	35
25	1.7	1.1	.6	35
	1971-75 (AGE 38-43)			
5	2.3	.7	1.6	70
10	1.6	.6	1.0	63
15	1.2	.5	.7	58
20	1.2	.6	.6	50
25	1.1	.7	.4	36
	1976-80 (AGE 43-48)			
5	1.5	0	1.5	100
10	1.1	0	1.1	100
15	.8	0	.8	100
20	.7	0	.7	100
25	.5	0	.5	100
	1981-85 (AGE 48-53)			
5	2.1	.9	1.2	57
10	1.0	.3	.7	70
15	1.0	.4	.6	60
20	1.1	.6	.5	46
25	.8	.3	.5	63
	1966-86 (AGE 33-53)			
5	9.8	3.7	6.1	62
10	6.7	2.8	3.9	58
15	5.7	2.7	3.0	53
20	5.0	2.5	2.5	50
25	4.1	2.1	2.0	49

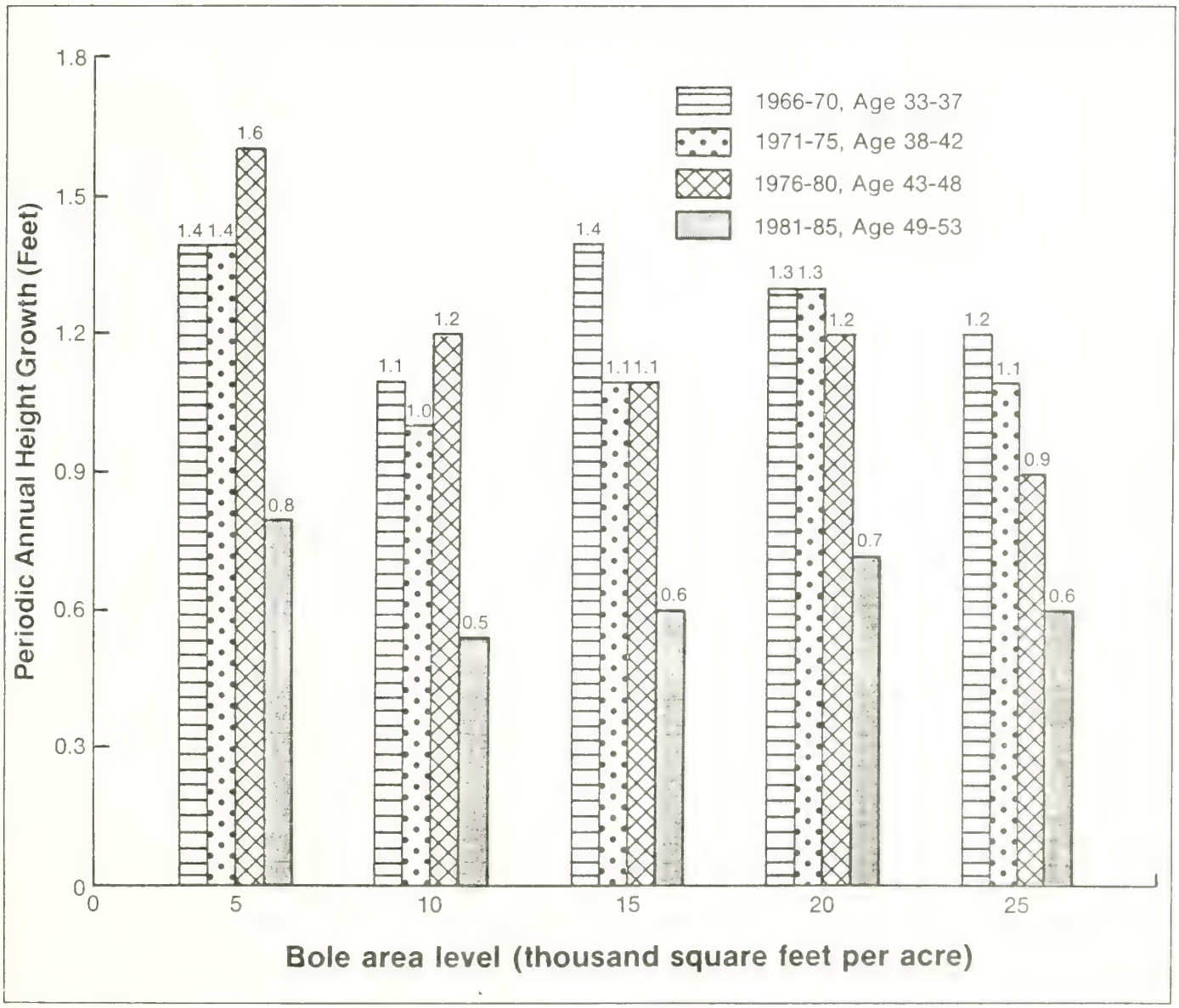


Figure 4—Periodic annual height growth by density level (bole area) and growth period.

Mortality

Mortality was light during the first 15 years of this study. Only 12 of 1,567 study trees died during the first period, 7 during the second period, and 3 during the third period; however, 58 trees died during the last 5 years of the study because the ice storm in 1984 broke tree boles below the live crown. All mortality occurred in the two highest density levels, except for 5 trees that died in a middle-density plot. Of the 1,567 trees present at the beginning of the study, 5 percent (80 trees) died during the 20 years of the study; 3.7 percent of this mortality was the result of the one ice storm in 1984. During the third period (1976-80), a light-to-moderate infestation of the larch case-bearer (*Coleophora laricella* (Hübner)) occurred on all plots.

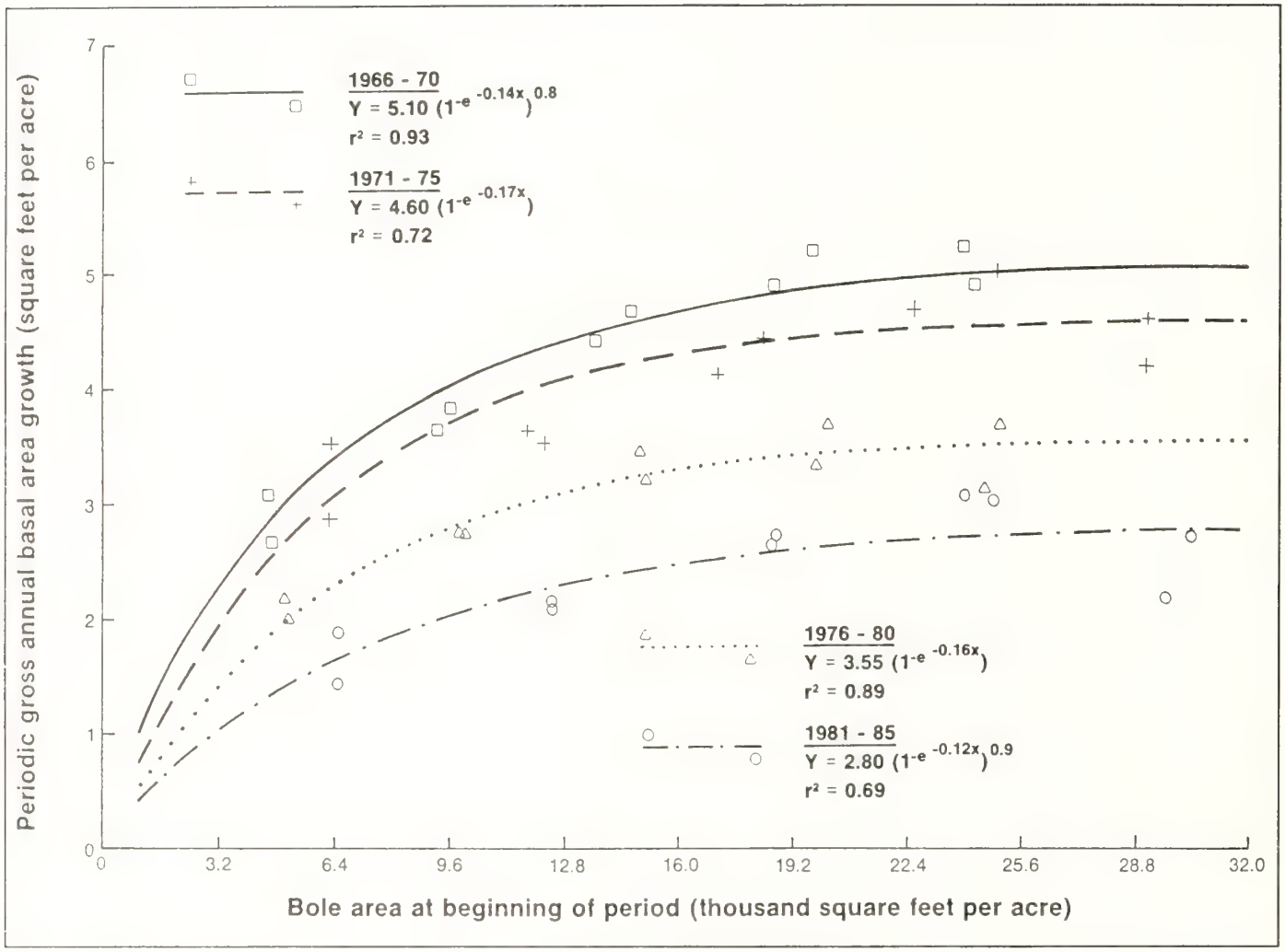


Figure 5—Periodic gross annual basal area growth by density level (bole area) and growth period.

Basal-Area Growth

Basal-area increment increased during all periods with increasing stand density, except for a slight decline at the highest density level during the last three periods (table 2). Differences in basal-area growth among density levels were significant ($P<0.01$). As expected, growth slowed significantly ($P<0.01$) from period to period as the stand became older (figs. 5 and 6). Averaged over all density levels, gross basal-area growth decreased from the first to the fourth period from 4.2 to 2.4 square feet per acre per year. During the fourth period, net basal-area growth at the highest density was almost zero because of the considerable mortality in these plots from the 1984 ice storm (table 2). Bole area and basal area were about equal as predictors of basal-area increment; each accounted for about 65 to 93 percent of the variation in growth. The interaction between stand density and growth period was also significant ($P<0.01$), primarily because of the increase in growth at the lowest density from the first to the second period in contrast to a decrease at the other four densities.

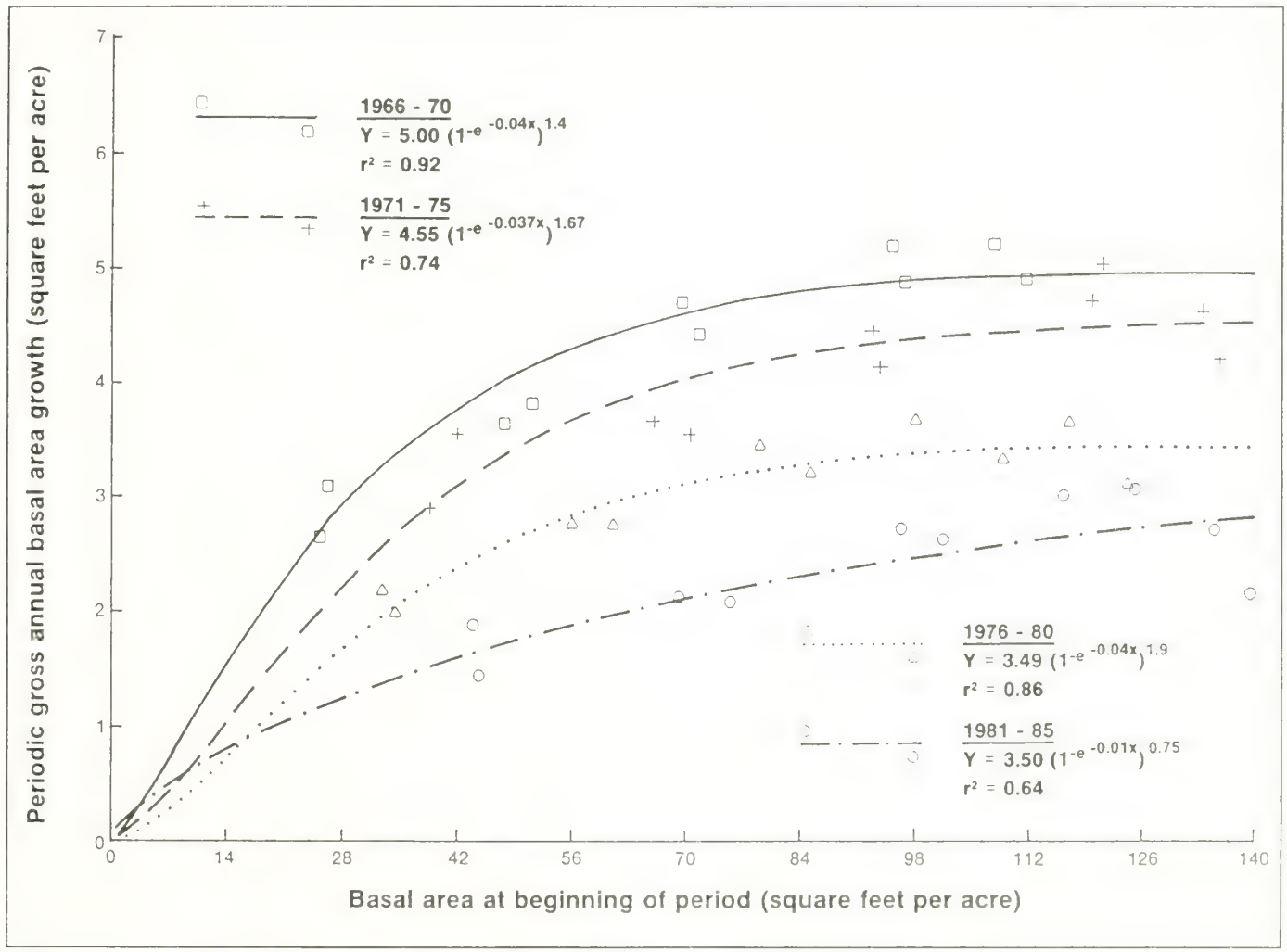


Figure 6—Periodic gross annual basal area growth by density level (basal area) and growth period.

Volume Growth

Total gross cubic-volume increment was excellent during the 20-year study, ranging from a low of 64 cubic feet per acre per year during the first period (level 1) to a high of 173 cubic feet per acre per year during the second period (level 4)(table 2). Gross and net volume growth were essentially the same except at levels 4 and 5 during the fourth period when net growth was reduced from 11 to 38 percent because of mortality from the ice storm. Averaged over all density levels, gross cubic increment increased significantly ($P<0.01$) from 104 cubic feet per acre per year during the first period to 134 cubic feet in the second period, declined slightly to 123 cubic feet during the third period, and to 114 cubic feet in the fourth period.

Gross volume growth increased in response to rising growing-stock levels during all periods (figs. 7 and 8). Although these curves show increasing growth over the range of stand densities tested, only a small increase in growth occurred from the fourth to the fifth density level compared to the more heavily thinned plots (table 2). This small increase suggests that full site use occurs as stand density approaches 30,000 square

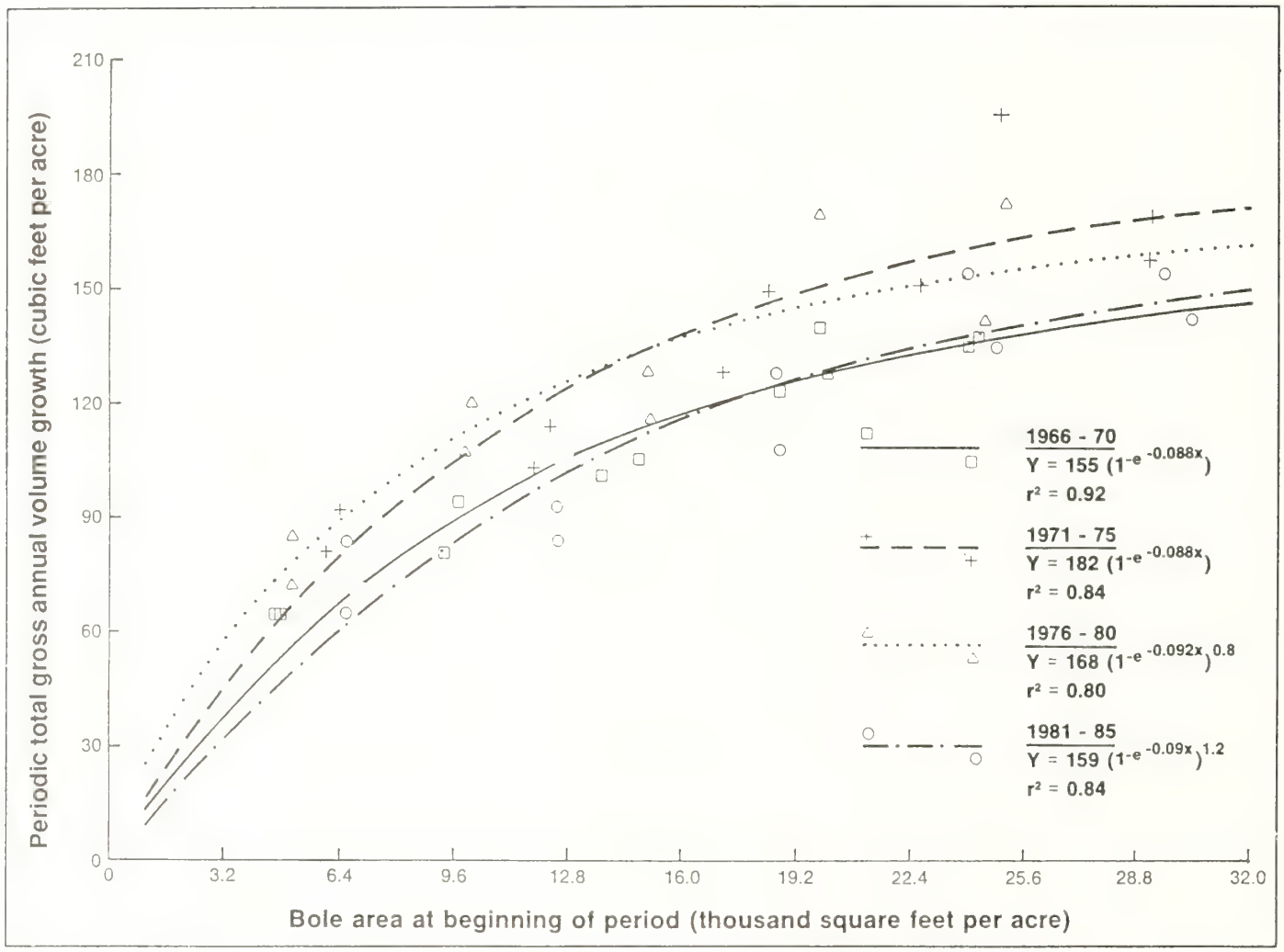


Figure 7—Periodic total gross annual cubic volume growth by density level (bole area) and growth period.

feet of bole area per acre and that increasing stocking beyond this level may not result in an increase in total volume increment. All growth differences among density levels were significant ($P<0.01$) except level 4 vs. level 5. Volume increment was about twice as great on the highest density plots as on the lowest during all periods; but much of the growth at high densities was distributed on more small, slow-growing trees.

Gross cubic-volume growth of the 75 largest trees per acre responded to stand density in the same manner as diameter growth did during all four periods—they grew faster at the lowest density level (table 2). Growth of these large trees was about twice as great at the lowest density than at the highest, which shows how growth is concentrated on the large trees in the low-density plots because of few competing trees.

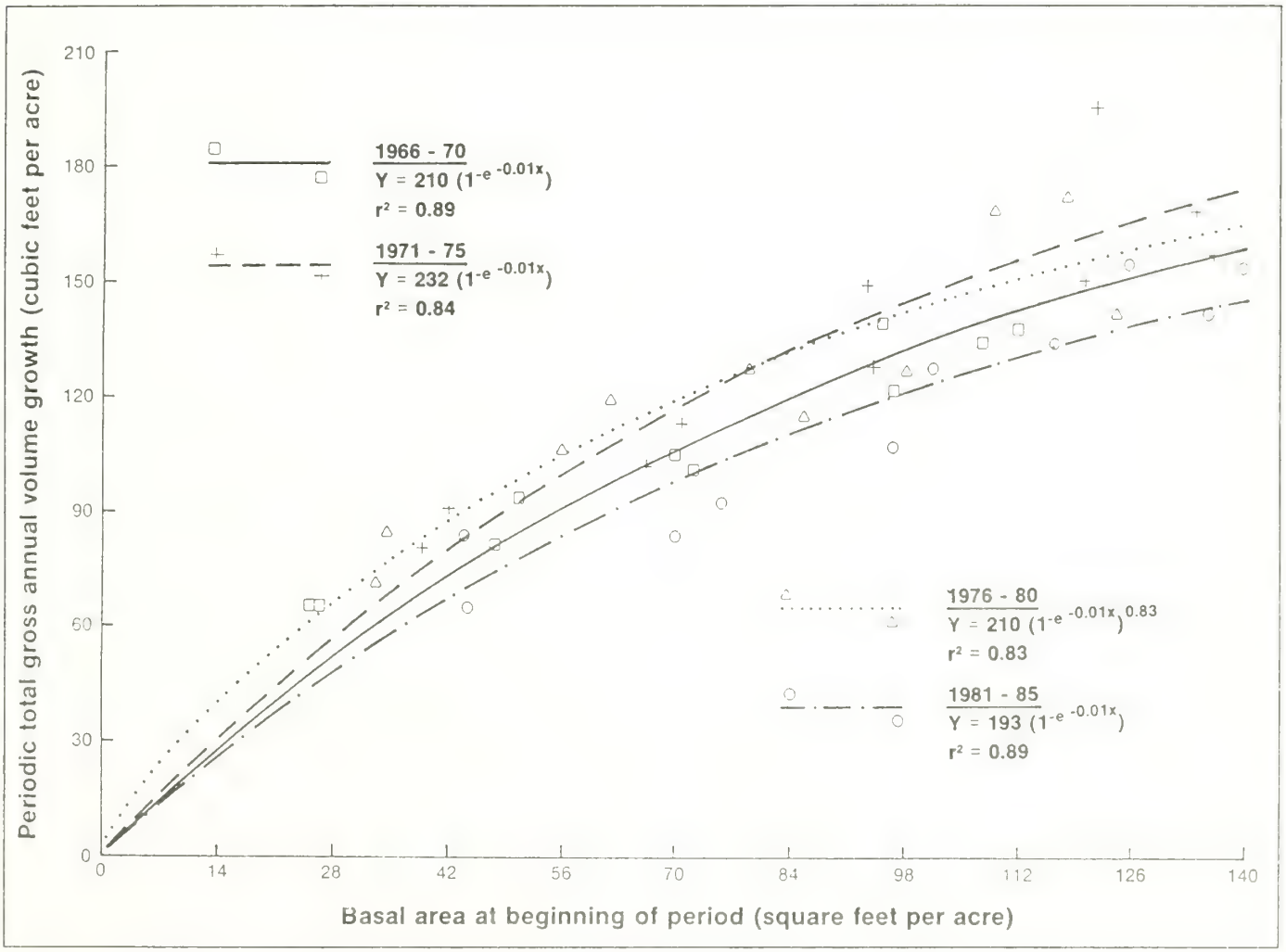


Figure 8—Periodic total gross annual cubic volume growth by density level (basal area) and growth period.

Board-foot volume increment increased from an average of 80 board feet per acre per year during the first period to 585 board feet per acre during the fourth period. All increases from period to period were significant ($P<0.01$). The more rapid diameter growth in low-density plots resulted in greater board-foot volume growth because more trees moved into merchantable size classes (ingrowth) and because of faster growth on trees already of saw-log size (10 inches d.b.h. or larger). Ingrowth accounted for about 90 percent of the board-foot volume growth during the first period and dropped to about 50 percent during the fourth period. Board-foot volume growth in the high-density plots is expected to increase rapidly in the future as many more trees reach saw-log size.

Mean annual cubic-foot increment is apparently nearing culmination (table 4), which agrees with data from yield tables for larch in Montana (Schmidt and others 1976) that show a 60- to 70-year culmination age.

Table 4—Net mean annual increment per acre of western larch by density level (bole area)

Bole-area level	Net mean annual increment by total age (years)				
	33	38	43	48	53
Thousand square feet per acre	*Cubic feet*				
5	60	61	64	65	66
10	69	72	76	80	80
15	72	76	83	87	89
20	70	78	89	95	98
25	67	75	85	93	93

Total Yield and Tree Size

Total net yield in cubic feet generally increased as stand density increased, although yield differences among the four highest levels were not large. In 1986, net yield ranged from 3,500 cubic feet per acre at the lowest density to 5,187 cubic feet at the second-highest and decreased slightly to 4,907 cubic feet at the highest (table 5). On the other hand, the greatest board-foot yield was at low stand densities and decreased considerably as stocking increased; the yields ranged from about 8,900 board feet per acre at the second-lowest density to about 3,000 board feet at the highest. Because essentially no board-foot volume was present on any of the plots at the beginning of the study, all the difference in yield can be attributed to the increased diameter growth at the low-density levels.

The quadratic mean diameter after thinning in 1986 ranged from 8.2 to 14.7 inches (tables 1 and 5). Because of differences in mean tree diameters, plots at the highest density contained more unmerchantable trees and, therefore, less merchantable volume from thinnings. For example, 41 trees per acre removed in the third thinning from the 10,000-square-foot density level yielded 1,719 board feet. In contrast, 95 trees per acre cut from the 25,000-square-foot level yielded only 129 board feet.

Table 5–Changes in number of trees, average diameter, cubic- and board-foot volumes (per acre), 1966 to 1986, resulting from 3 thinnings, by density level (bole area)

Item	Residual bole-area level (thousand square feet)				
	5	10	15	20	25
			Number of trees		
Total trees, 1966	924	1,161	1,406	1,377	1,459
Cut, 1966	828	946	1,051	831	714
Left, 1966	96	215	355	546	745
Cut, 1976	45	86	130	213	281
Left, 1976	51	129	225	333	464
Cut, 1986	19	41	73	100	95
Left, 1986	32	87	148	218	313
20-year mortality	0	1	4	15	56
			Inches		
Quadratic mean diameter after thinning in 1986	14.7	11.3	10.0	9.4	8.2
			Percent		
Trees 10 inches d.b.h. and larger after thinning in 1986	100	89.2	45.9	30.3	11.0
			Cubic feet		
Total volume:					
Total stand, 1966	1,995	2,287	2,367	2,322	2,200
Cut , 1966	1,521	1,385	1,095	706	353
Left, 1966	474	902	1,272	1,616	1,847
Cut, 1976	462	569	663	855	696
Left, 1976	760	1,301	1,808	2,248	2,621
Cut, 1986	449	623	756	848	617
Left, 1986	1,065	1,671	2,206	2,776	3,241
Net 20-year growth	1,505	1,959	2,353	2,865	2,707
Total net yield, 1986	3,500	4,246	4,720	5,187	4,907
			Board feet		
Merchantable volume:					
Total stand, 1966	48	0	193	0	0
Cut, 1966	0	0	0	0	0
Left, 1966	48	0	193	0	0
Cut, 1976	778	0	0	0	0
Left, 1976	2,876	2,366	1,464	1,168	706
Cut, 1986	2,120	1,719	1,053	359	129
Left, 1986	5,463	7,197	6,200	5,269	2,899
Net 20-year growth	8,315	8,914	7,060	5,627	3,040
Total net yield, 1986	8,363	8,914	7,253	5,627	3,040

Management Implications

After 20 years, this study clearly demonstrates the benefits of thinning from below so that growth is concentrated on a few, fast-growing trees. The diameter growth increased as stand density decreased, and the larger, more vigorous trees in these plots were better able to survive wind, snow, and ice storms than were the small trees.

Because the greatest diameter growth occurred at low stand densities and the greatest cubic volume growth at high densities, it is not possible to maximize both at the same time. The primary timber-management objective of precommercial thinning should be to stimulate diameter growth of residual trees so that merchantable products may be harvested sooner. Therefore, the stocking level left after precommercial thinning should depend on the manager's estimate of the minimum size tree (d.b.h.) that will be merchantable in the future. If markets for small trees exist and frequent commercial thinnings are possible to salvage dead trees, a high stand density is indicated to take advantage of the productive capacity of the site. If, on the other hand, no pulpwood market exists and the management objectives are to shorten the rotation and increase water and forage yields, a heavier precommercial thinning is necessary—with a sacrifice of some volume growth.

Because of the shade-intolerant nature of western larch, early thinning results in the greatest gains. Competition in young, overstocked larch stands results in reduction of the live crown followed by a decrease in diameter and height growth. Small, low-vigor trees also are less resistant to damage from wind, snow, insects, and diseases than are trees having adequate growing space. The ideal time for precommercial thinning of larch is when the trees are 10 to 15 years old and 10 to 15 feet tall. Care should be taken when thinning to cut trees below the lowest live branch to avoid having branches turn up.

After a stand has reached merchantable size, management goals should be to optimize volume and diameter growth and to salvage dead trees. Regulation of density in merchantable stands can be accomplished by applying the stocking-level curves for larch (Cochran 1985). These curves show that acceptable stocking levels include a wide range of stand densities; the choice depends on management objectives. It is therefore not critical to maintain an exact density at any time in the rotation, but rather to thin young stands to prevent excessive competition, which results in small crowns, loss of vigor, reduced growth, and increased mortality.

Conclusions

Early precommercial thinnings, when trees are 10 to 15 years old and 10 to 15 feet tall, are recommended for overstocked stands of larch. The selected spacing should result in a diameter growth rate that will allow merchantable trees to be cut in the next (commercial) thinning. By selecting a narrow spacing, the silviculturist is assuming that small trees will be salable at the time of the commercial thinning; conversely, by selecting a wide spacing one assumes that large trees are needed for the commercial thinning. After the stand reaches merchantable size, thinning from below to reduce basal area to the minimum stocking-level curve is recommended (Cochran 1985).

Metric Conversions

1 mile = 1.61 kilometers

1 foot = 0.3048 meter

1 inch = 2.54 centimeters

1 acre = 0.4047 hectare

1 square foot/acre = 0.2296 square meter/hectare

1 cubic foot/acre = 0.0700 cubic meter/hectare

1 tree/acre = 2.47 trees/hectare

Literature Cited

Cochran, P.H. 1985. Site index, height growth, normal yields, and stocking levels for larch in Oregon and Washington. Res. Note PNW-424. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 24 p.

Cole, Dennis M. 1984. Crop-tree thinning a 50-year-old western larch stand: 25-year results. Res. Pap. INT-328. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 9 p.

Franklin, Jerry F; Dyrness, C.T. 1973. Natural vegetation of Oregon and Washington. Gen. Tech. Rep. PNW-8. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 417 p.

Illingworth, K. 1964. Crop-tree thinning of western larch. British Columbia Forest Service Research Review for 1964: 52.

Lexen, Bert. 1943. Bole area as an expression of growing stock. Journal of Forestry. 41(12): 883-885.

Roe, Arthur L.; Schmidt, Wyman C. 1965. Thinning western larch. Res. Pap. INT-16. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 10 p.

Schmidt, Wyman C. 1966. Growth opportunities for young western larch. Res. Note INT-50. Odgen, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 4 p.

Schmidt, Wyman C.; Shearer, Raymond C.; Roe, Arthur L. 1976. Ecology and silviculture of western larch forests. Tech. Bull. 1520. Washington, DC: U.S. Department of Agriculture. 96 p.

Seidel, K.W. 1971. Growth of young even-aged western larch stands after thinning in eastern Oregon. Res. Note PNW-165. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 12 p.

Seidel, K.W. 1977. Levels-of-growing-stock study in thinned western larch pole stands in eastern Oregon. Res. Pap. PNW-221. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 14 p.

Seidel, K.W. 1982. Growth and yield of western larch: 15-year results of a levels-of-growing-stock study. Res. Note PNW-398. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 14 p.

Smith, David Martyn. 1962. The practice of silviculture. 7th ed. New York: John Wiley & Sons, Inc. 578 p.

Thompson, C.F. 1969. Crop-tree thinning of western larch. British Columbia Forest Service Review: 94.

Seidel, K.W. 1987. Results after 20 years from a western larch levels-of-growing-stock study. Res. Pap. PNW-RP-387. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 18 p.

The 20-year growth response from a levels-of-growing-stock study in an even-aged western larch stand in eastern Oregon, first thinned at age 33, showed that trees growing at low stand densities grew more rapidly in diameter than trees in high-density plots. Height growth was relatively uniform among density levels. Both basal-area and total cubic-volume increment increased as stand density increased. Despite the large reduction in volume increment at the low densities, most of the wood is concentrated on a few, fast-growing trees that can reach usable size sooner than slow-growing trees in high-density plots.

Keywords: Increment (stand volume), even-aged stands, stand density, thinning effects, growing stock (-increment/yield, western larch, *Larix occidentalis.*

The **Forest Service** of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing nation.

The U.S. Department of Agriculture is an Equal Opportunity Employer. Applicants for all Department programs will be given equal consideration without regard to race, color, sex, religion, or national origin.

Pacific Northwest Research Station
319 S.W. Pine St.
P. O. Box 3890
Portland, Oregon 97208

November 1987

U.S. Department of Agriculture
Pacific Northwest Research Station
319 S.W. Pine Street
P.O. Box 3890
Portland, Oregon 97208

BULK RATE
POSTAGE +
FEES PAID
USDA-FS
PERMIT No. G-40

Official Business
Penalty for Private Use, $300

do NOT detach label

United States
Department of
Agriculture

Forest Service

Pacific Northwest
Research Station

Research Paper
PNW-RP-388

Changes in Water Quality and Climate After Forest Harvest in Central Washington State

W.B. Fowler, T.D. Anderson, and J.D. Helvey

Authors

W.B. FOWLER was principal research meteorologist (now retired) and T.D. ANDERSON is a chemist at Forestry Sciences Laboratory, 1133 N. Western Avenue, Wenatchee, Washington 98801; and J.D. HELVEY is supervisory research hydrologist at the Northeastern Forest Experiment Station, Timber and Watershed Laboratory, Box 445, Parsons, West Virginia 26287.

Abstract

Fowler, W.B.; Anderson, T.D.; Helvey, J.D. 1988. Changes in water quality and climate after forest harvest in central Washington State. Res. Pap. PNW-RP-388. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 12 p.

Chemical output of nitrate, calcium, magnesium, sodium, potassium, and organic nitrogen were determined on a grams-per-hectare-per-day basis for five treatment watersheds and a control watershed. Water samples were collected from April to October during 3 pretreatment and 3 posttreatment years (1978 to 1983). Except for increased calcium and sodium in several streams, regression equations comparing treatment with control showed no significant difference for pretreatment and posttreatment output. Output generally declined in the posttreatment years. Cyclic changes in output from these and other streams in the eastern Cascade Range in Washington appeared to occur regardless of treatment and were probably related to precipitation. Mean maximum air temperature increased during the posttreatment period in all the small watersheds, but stream temperatures were relatively unaffected.

Keywords: Water quality, sediment production, temperature, logging effects, Washington.

Research Summary

Information about baseline chemical output of streams and changes after timber harvest is limited for the forest zones of central Washington State. This study examined chemical output, climatic change, and turbidity and sediment production after longspan skyline and helicopter logging in four 34- to 169-ha subwatersheds, a main 969-ha watershed, and a 548-ha control watershed. The watersheds were near Wenatchee, Washington. Elevations ranged from 550 to 2130 m, and soil parent materials were ultrabasic metamorphics, overlaid with glacial till in some subwatersheds. Average annual precipitation was about 125 cm.

Water samples were collected from April to October during 3 pretreatment and 3 posttreatment years, 1978 to 1983. Chemical output of nitrate, calcium, magnesium, sodium, potassium, and organic nitrogen were determined on a grams-per-hectare-per-day basis. Mean values for the 6-year period, except for calcium and magnesium, were comparable to values for the Entiat Experimental Forest watersheds and an uncut watershed (Andrews Creek) in the Pasayten Wilderness also located on the east slopes of the Cascade Range. Output of calcium from these small streams was about 5 times higher and magnesium about 20 times higher. Comparing treatment with control, study watersheds showed no significant difference for pretreatment and posttreatment output except for increased calcium and sodium in several streams. Output generally declined in the posttreatment years. Cyclic changes in output from these and other streams appeared to occur regardless of treatment and were probably related to precipitation.

Turbidity and suspended sediment were measured at one location where road construction occurred and at the main gauging station lower on the stream. During high flow, peaks in sediment and turbidity at the main gauging station followed road construction upstream. Sediment accumulated in the stream channel during the low-flow period and was not observed until the next runoff season.

Mean maximum air temperature increased during the posttreatment period in all the small watersheds, but stream temperatures were relatively unaffected. Cooling of stream water below a reconstructed stream crossing was an anomaly.

Contents

1 **Introduction**

1 **Methods**

1 Watershed Characteristics

3 Watershed Treatments

4 Climate and Streamflow

5 **Results and Discussion**

5 Water Quality

9 Air and Water Temperatures

10 Effects of Road Construction on Sediment and Turbidity

11 **Conclusions**

11 **English Equivalents**

12 **Literature Cited**

Introduction

High-quality water from forested watersheds on the eastern slopes of the Cascade Range in Washington and Oregon supports a multimillion dollar irrigation economy, provides domestic water supplies, and maintains the aquatic habitat for a valuable local and anadromous fishery. Perceived changes in streamflow quality or quantity ascribed to forest management may invite judicial action and present a custodial challenge in achieving multiple use of these lands.

Watershed studies within this forest zone are limited. Watersheds in the Entiat Experimental Forest in central Washington State were to have addressed the question of how logging systems could be designed to minimize hydrologic impacts (Helvey and others 1976a). Wildfire in the early 1970's, however, changed the mission of the Entiat Experimental Forest to documenting wildfire effects and monitoring rehabilitation efforts (Helvey and others 1976b). Tiedemann and others (1978) described the nutrient economy of the Entiat streams for the postfire years of 1971 to 1975 and provided some benchmark nutrient output levels. Unfortunately, only a limited record existed for the prefire period.

The continued need for information on watershed processes under management led to selection of the Hansel Creek and Allen Creek watersheds, the first of a series of new watersheds to be studied. Although 20 watershed complexes were identified for an extensive study of the effects of forest harvest on water quality and yield, only the Hansel and Allen watersheds were developed. This report presents a case history of the changes in streamflow quality and climate of these watersheds as affected by forest harvest.

The Andrews Creek watershed in the Pasayten Wilderness has been monitored since 1975 by the U.S. Geological Survey, U.S. Department of the Interior, for flow and nutrient concentrations. Computed nutrient output from this uncut watershed provided a contemporary record for comparison with this study.

Methods

Watershed Characteristics

The watershed complex (fig. 1) is about 30 km west of Wenatchee in central Washington State. The two major gauged watersheds, Allen Creek (number 7)--the control--and Hansel Creek (number 1), flow easterly from the Mount Stuart Range into the Wenatchee and Columbia River drainages. Table 1 shows total area, percentage treated, and range in elevation of the main and subwatersheds. Portions of four subwatersheds (Hansel 2, 3, 4, and 5) were clearcut; Hansel 6 was not treated.

These watersheds are in the contact zone between the granitic materials of the Stuart Range to the west and the Swauk sandstones to the east. Ultrabasic serpentine and schist are parent materials with rock outcrops of granite and sandstones at upper and lower boundaries, respectively. Glacial till covers schist in watershed numbers 4, 5, and 6. Soils are sandy to loamy, with depths to 1.5 m. McColley (1976) identifies 11 soil types in these watersheds.

Prelogging vegetation consisted of ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western larch (*Larix occidentalis* Nutt.), and western white pine (*Pinus monticola* Dougl. ex D. Don) on the south- and west-facing slopes and a gradation to grand fir (*Abies amabilis* Dougl ex Forbes) and Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) on the east-facing slopes. Areas not covered by trees, rock outcrops, and fringes of grassy slopes occupied about 15 percent of the area, mainly the upper elevations in watersheds 2 and 3.

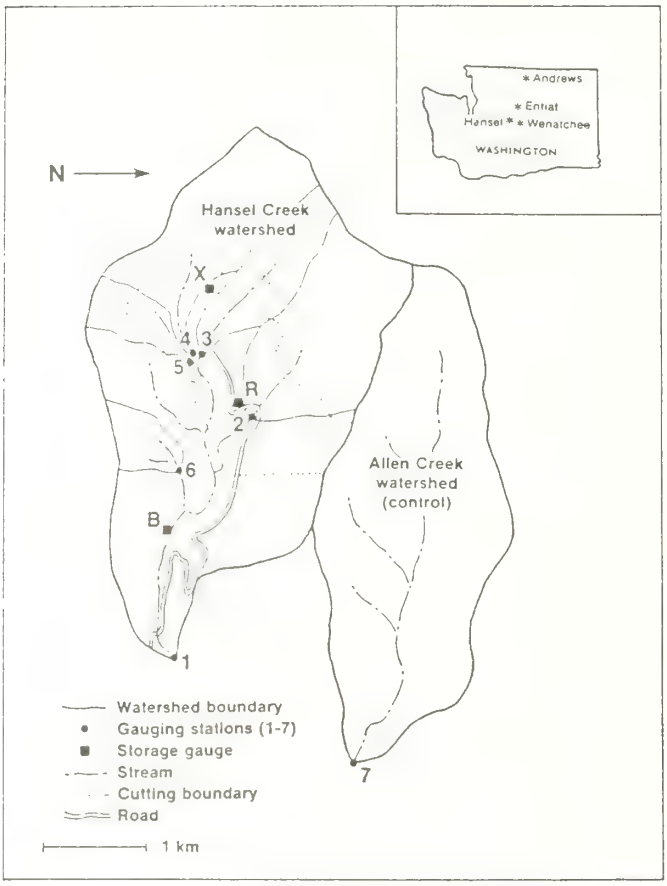


Figure 1--Study area. Inset map shows locations of Hansel watersheds, the Entiat Experimental Forest, and Andrews Creek in Washington State.

Table 1--Characteristics of Hansel Creek and Allen Creek watersheds

Watershed number and name	Elevation		Area	Percentage treated
	Maximum	Minimum		
	Meters		Hectares	
1. Hansel 1	731	2133	869	[1/] 26
2. Hansel 2	1075	2098	169	22
3. Hansel 3	1161	2132	82	39
4. Hansel 4	1160	2133	167	22
5. Hansel 5	1158	1673	34	47
6. Hansel 6	969	1417	31	0
7. Allen	548	2011	539	0

[1/] An additional 23 percent had been removed in an earlier harvest.

The lower portion, about 160 ha of the Hansel watershed, is private land. This area was harvested in the 1960's. The main hauling road through this area was reconstructed in 1979, along with the access road into the Wenatchee National Forest, USDA Forest Service, section.

Watershed Treatments

Timing was as follows:

Activity	Period
Weirs and instruments installed	Summer to winter 1977
Roads reconstructed	Summer to fall 1979
Timber harvest	Summer 1980 to summer 1981
Instruments removed	Fall 1983

An earlier pioneering road had crossed the stream in watershed 2. This (about 1 km) section was reconstructed, and an additional 1 km of new road ended at the helicopter-landing area above the gauging station in watershed 3.

Erosion hazard was recognized by the Forest Service as moderate to high. Selection of major logging methods--helicopter and longspan skyline--reflected this concern. The original combination of logging methods was to have been 77 to 92 percent helicopter and as much as 13 percent longspan skyline. Small areas of relatively flat ground below the small watersheds were suitable for shortspan skyline. Some areas were logged by helicopter in the fall of 1980, but a falling timber market made continued helicopter yarding uneconomical. The majority of yarding was done with the longspan system. No distinction is made in this analysis between logging methods--helicopter or longspan skyline. Blowdown of many leave trees in the "longspan" area further reduced its sparse residual overstory. During the hiatus between the two logging methods, about 2500 m^3 of downed material overwintered for 2 years on watersheds 3, 4, and 5. This material was removed in 1982. On the Wenatchee National Forest, best management practices required directional felling (away from the stream) in a variable width riparian zone and no ground yarding across the active stream channels. Logging residue was not treated.

Harvested areas are indicated in figure 1. The original sale included the area between watersheds 5 and 6, and watershed 6, in the harvest. Soils in this area, however, were not suitable for road construction, and the change to the longspan skyline precluded harvest.

Volume removed totaled 13 850 m^3, distributed as follows:

Species	Volume (m^3)
Douglas-fir	7400
Grand fir	4200
Ponderosa pine	1550
Western larch	450
Western white pine	150
Engelmann spruce	100

Table 2--Water years precipitation based on storage gauges in Hansel Creek

Water year	Storage gauge (elevation)		
	X (1316 m)	R (1133 m)	B (875 m)
	Centimeters		
1979	73.0	68.7	56.6
1980	154.0	140.6	84.3
1981	167.7	135.0	80.3
1982	195.5	175.0	96.2
1983	172.2	169.9	98.8
Mean	152.9	137.8	83.3

Climate and Streamflow

These watersheds have a precipitation regime of winter maximum and summer minimum common to the Pacific Northwest. Expected precipitation in both November and December is 25 to 35 cm. Annual precipitation totals from the three storage gauges in Hansel Creek (X, R, and B in fig. 1) are shown in table 2. Almost twice as much precipitation was recorded at the uppermost (1316 m) gauge (X in fig. 1) than at the bottom (835 m) gauge (B in fig. 1). Precipitation during the 1979 water year was only about one-half the average annual for gauges R (1133 m) and X. Gauge B received about 70 percent of the mean amount in water year 1979. Precipitation was not measured in Allen Creek. Based on nearby stations (at 12-km distance), summer precipitation decreases to an average of about 0.75 cm in the least rainy month, August. Zero precipitation was recorded in some months. Occasional rain-on-snow events resulted in extremely high stream flows. The gauging station in Allen Creek was destroyed in water year 1980 during one of these events. Snow is, however, the predominant form of winter precipitation; maximum depths of 2 m can be expected, with maximum snowpack water content in late April.

Air temperature was monitored at stream gauging stations 2 to 6 in Hansel Creek and at the storage gauges B and R. Temperature was recorded as a 3-hour average. Resolution and accuracy of these recording thermometers was $\pm 0.2\ ^{\circ}C$. The maximum temperature recorded was 35.4 $^{\circ}C$ on the exposed ridgeline at storage gauge R. Minimum temperatures below -10 $^{\circ}C$ (the limit for this instrument) occurred in all winters. Stream temperature was monitored at all gauging stations, except Allen Creek. Maximum stream temperature did not exceed 13 $^{\circ}C$. Minimum temperature for all the streams was 0 $^{\circ}C$.

Streamflow was monitored at each gauging station with "H" flumes manufactured to the specifications of Holtan and others (1962). Water stage was measured from April 1 to September 30 with Fisher-Porter[1] digital recorders. High avalanche hazard, roads not suitable for winter access over snow, and freezing of control sections and stilling wells made winter (low flow) recording from these streams infeasible.

[1] The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture of any product or service to the exclusion of others that may be suitable.

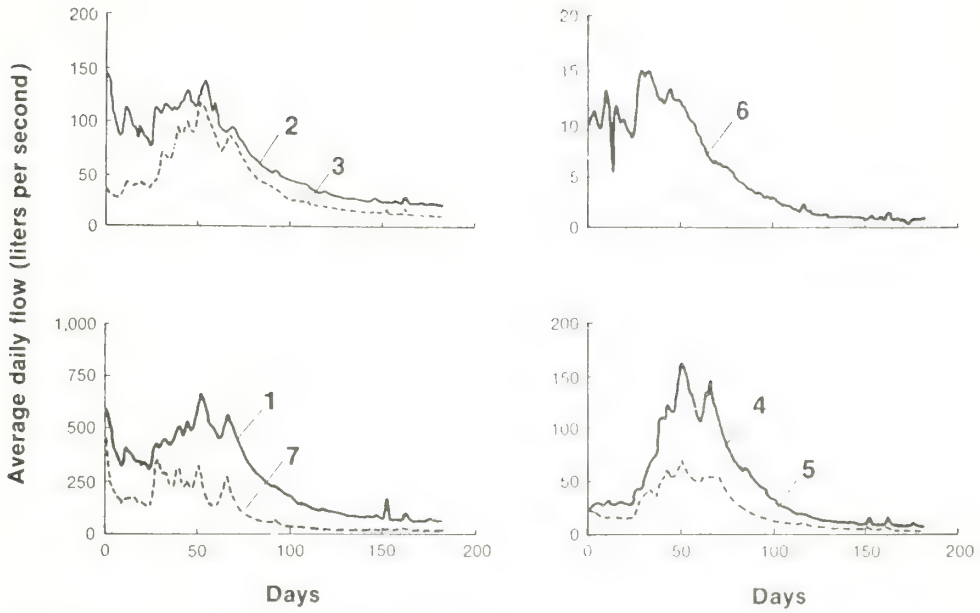


Figure 2--Seasonal runoff patterns for the Hansel Creek streams (1 to 6) and Allen Creek (7), April 1 to September 30, 1978.

Figure 2 presents the average daily flow, based on the 0600- and 1800-hour recordings, from April 1 to September 30, 1978. From the more southerly exposed watershed (2) or where the lower elevation lands were included (for example, the entire watershed complex of Allen Creek (7) or Hansel Creek (1)), flows were already well elevated in April. Watersheds 3, 4, and 5 represented the higher elevation, easterly exposures, and streamflows peaked at the end of May into early June.

Pump samplers operating on an hourly cycle provided an integrated sediment sample at three locations within the Hansel Creek watershed. Samples in watershed 2 were taken 50 m above the road construction, 100 m below the construction, and at the main stream gauging site (1).

Results and Discussion

Water Quality

Water yield (streamflow) data were required for evaluating the changing nutrient status of these watersheds. Thirty-eight flow periods were constructed from the average daily flow records, with midpoints of each period corresponding to the sampling dates for instream physical and chemical components. There were 23 pretreatment and 15 posttreatment periods. The physical properties pH, turbidity, suspended sediment, and conductivity were determined from the water samples. Chemical analysis was for nitrate-N (NO_3-N), calcium (Ca^{++}), magnesium (Mg^{++}), sodium (Na^{+}), potassium (K^{+}), and organic nitrogen.[2]

[2] Samples were analyzed for: nitrate-N (NO^3) by cadmium reduction (Wood and others 1967); dissolved and suspended organic nitrogen by Kjeldahl digestion (Chapman and Pratt 1961) with phenolhypochlorite determination of ammonia; Ca^{++}, Mg^{++}, K^{+}, and Na^{+} by atomic absorption spectroscopy (Robinson 1966); pH by glass electrode method; and conductivity by conductivity meter (Golterman and Clymo 1969)

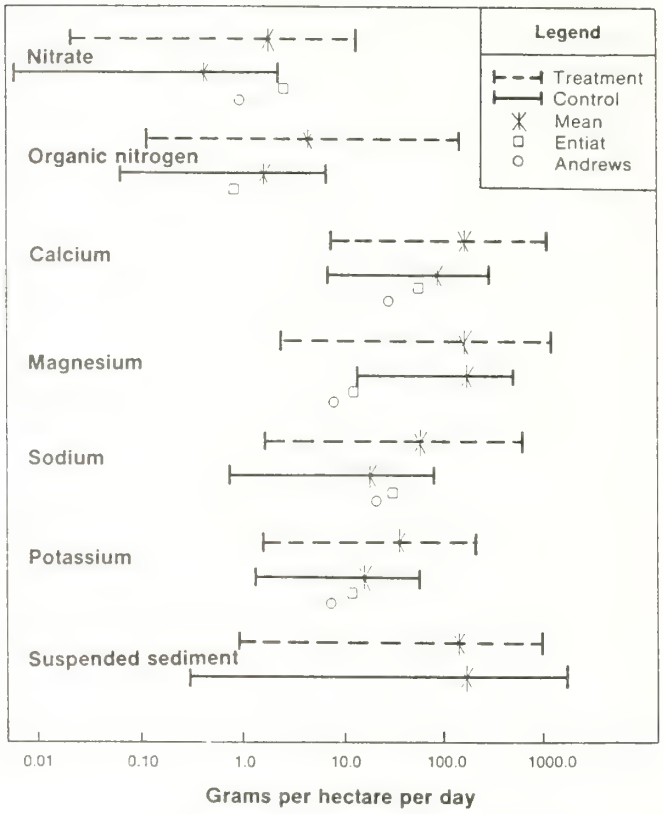


Figure 3--Means and ranges of chemical output from treatment stream (Hansel 2 to 5) and control (Allen Creek) for years 1978 to 1981. Mean values for the Entiat Experimental Forest watersheds and Andrews Creek are also shown.

Figure 3 presents on a logarithmic scale the means and ranges of the combined chemical output from the treatment watersheds (Hansel Creek numbers 2 to 5) and the control watershed (Allen Creek) for all sample periods. For comparison with other east Cascade watersheds, average chemical output from the three Entiat Experimental Forest watersheds from 1971 to 1975 and from the Andrews Creek watershed from 1975 to 1982 is shown. Suspended sediment data were not available from these latter watersheds or for organic nitrogen from Andrews Creek. A variation of more than three orders of magnitude (a thousand times) is shown in the range of the Hansel and Allen Creek data. The mean values are, however, relatively similar between the several watersheds, considering that the watershed areas range from 34 ha in Hansel 5, to 1551 ha for the combined Entiat watersheds, and to 5714 ha for Andrews Creek. Calcium and magnesium output reflect the ultrabasic parent materials in Hansel and Allen Creeks; mean values for magnesium were 20 times higher than in Andrews Creek.

The most rigorous test of the treatment effects in these watersheds is to compare the slopes and levels of the regressions of chemical outputs developed for treatment-control pairs for pretreatment and posttreatment periods. For the 7 variables shown in figure 3 and the 5 treatment-control pairs, 35 combinations were examined. Of these, only calcium in watersheds 3 and 5 and sodium in watershed 3 showed statistically significant ($P<0.05$) changes (increases) in chemical output compared with the control (table 3). Figure 4 shows the calcium output from watersheds 3 and 7 (control). The calcium output from 3 is essentially equal in the two periods--changing level and slope of the regression equations result from decreased posttreatment output of calcium from the control watershed.

Table 3--Regression equations for properties of streams 3 and 5 found significantly different[1] in pretreatment and posttreatment periods compared with stream 7

Chemical and stream	Mean	Regression	r^2	Mean	Regression	
	Grams per hectare per day					
Calcium:						
Stream 3 (Hansel)	142.79	Y = 77.14 + 0.716(#7)	[illegible]	140.70	Y = [illegible] + 1.291(#7)	
Stream 7 (Allen)	91.56			73.29		
Stream 5 (Hansel)	308.98	Y = 79.20 + 2.387(#7)	.55	332.01	Y = -2.87 + 5.296(#7)	83
Stream 7 (Allen)	96.23			63.23		
Sodium:						
Stream 3 (Hansel)	64.97	Y = 31.39 + 1.421(#7)	.61	54.76	Y = 19.45 + 3.155(#7)	84
Stream 7 (Allen)	23.77			11.19		

[1] Test for common levels and slopes:
Calcium:
Streams 3 and 7. F = 5.51, P = 0.01
Streams 5 and 7. F = 4.21, P = 0.02
Sodium:
Streams 3 and 7. F = 5.06, P = 0.01

The chemical output from watersheds in this geographic area is not constant but varies during the season and among years. This is evident for the calcium output of study streams (fig. 4) and of Andrews Creek (fig. 5). Water year chemical output from Andrews Creek showed a strong relation to yearly precipitation. (Calcium correlated best, $r^2 = 0.93$, followed by sodium, magnesium, and potassium.) As watersheds become smaller, the correlation of chemical outputs to amount of precipitation and the correlation between individual watersheds decrease.

Averages for chemical output for two 3-year periods from Andrews Creek (1975-77, 1978-80) and one 2-year period (1981-82) showed calcium, sodium, and potassium highest from 1978 to 1980; magnesium was highest in 1980 and 1981; and potassium as much as three times higher in 1978-80 compared with the earlier or the later period. Outputs of chemicals and suspended sediments also were highest from the Hansel and Allen watersheds in the 1978-80 pretreatment period and lower in the 1981-83 posttreatment period. Similar variability in yearly output was also reported in the Entiat study (Tiedemann and others 1978). Although nitrate output in all years after the Entiat fire was higher than in the single prefire year, a five-time variability in postfire mean annual rates was shown. For metallic ions the 2d year after the fire, magnesium and sodium output rates were essentially equal to their prefire values; but calcium and potassium were only about 50 percent of their prefire values.

Although most studies of nitrate output after clearcutting show an increase at least the 1st year, some increases are relatively small or are not detected (Vitovsek and Melillo 1979). Martin and others (1984) examined 56 watersheds in New England and found only minor changes in stream chemistry attributable to normal timber harvest. Effects were masked by the buffering action of uncut areas or riparian zones

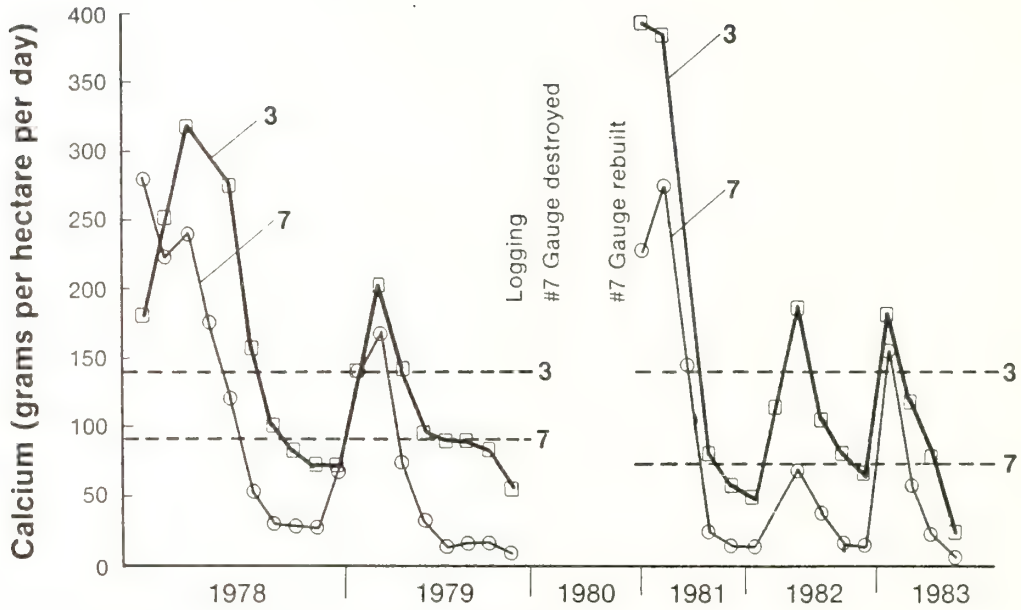


Figure 4--Daily and mean output of calcium for Hansel watershed 3 and control (7, Allen Creek), 1978-83.

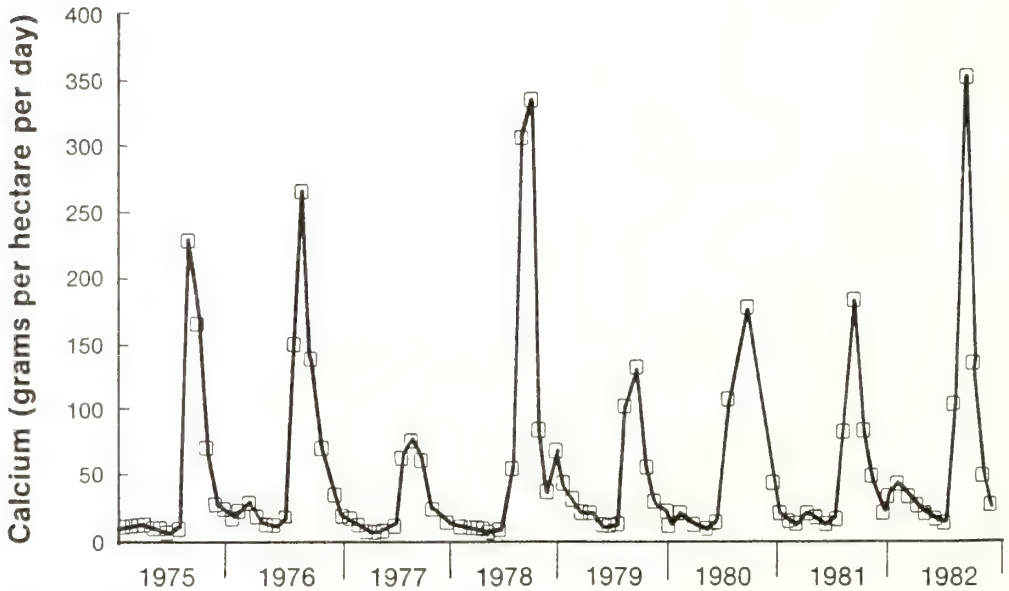


Figure 5--Calcium output for Andrews Creek, 1975 to 1982. Squares are instantaneous values at sampling times.

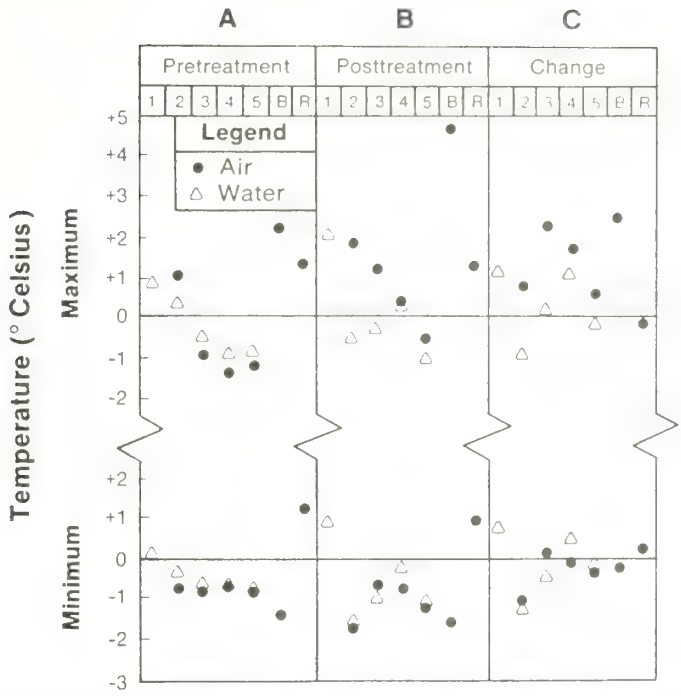


Figure 6--Pretreatment differences and relative change with treatment in mean maximum and mean minimum temperatures between uncut (watershed 6) and treatment watersheds (1, 2, 3, 4, and 5), storage gauge B, and storage gauge R Air temperature was not measured at number 1 gauge in Hansel Creek watershed.

Air and Water Temperatures

Figure 6, column A, presents pretreatment differences between the mean daily maximum and minimum air and water temperatures compared with temperatures in uncut watershed 6. Column B shows the posttreatment temperature differences and column C the relative changes. In column A, some stream and air temperatures were initially colder (numbers 3, 4, and 5) or warmer (2) and remained so after harvest (column B). Maximum air temperatures at all locations were warmer in the posttreatment period except for the ridgeline (R), which showed no change. Temperatures increased as much as 2.6 °C after insolation increased because of canopy removal. Exposure of the ridgeline location was unchanged. Minimum air temperatures, except for watershed 2 (colder), changed relatively little.

Maximum water temperatures increased by about 1 °C for streams 1 and 4 but showed no change for streams 3 and 5. The maximum for stream 2 was about 1 °C cooler in the posttreatment period. Minimum temperatures showed only small changes, less than ± 1 °C in the long-term average, except for stream 2, which was about 1.5 °C cooler.

The decreases in stream 2 temperature, both maximum and minimum, below the road construction was anomalous. Changes in sunlight absorption by the newly transported, lighter colored streambed materials, position of the sensor in the stream cross section, or decreased exposure by shading from rapidly growing riparian vegetation all probably contributed to the decreases.

Table 4--Average suspended sediment and turbidity in stream 2 above road construction (A), below road construction (B), and at Hansel Creek main station 1 (M), by sampling period

Year	Suspended sediment			Turbidity		
	A	B	M	A	B	M
	Milligrams per liter			NTU [1/]		
5/18 to 8/27, 1979:						
Before road construction	3.65	3.72	5.31	0.92	0.96	1.15
After road construction	3.54	178.06	4.75	.95	24.18	1.80
4/23 to 8/20, 1980	5.74	8.53	20.77	1.16	1.31	1.98
5/12 to 10/16, 1981	2.63	2.10	4.30	1.18	1.01	1.43

[1/] Nephlometric Turbidity Units.

Effects of Road Construction on Sediment and Turbidity

Table 4 shows the mean values of suspended sediment and turbidity near the road construction site in Hansel Creek from 1979 to 1981. Figures 7 and 8 present the 1979 chronology. Nothing about the suspended sediment or turbidity during the preconstruction period was remarkable. The initial peaks of both suspended sediment and turbidity during road construction were followed rapidly by a peak at the main stream site. By early August 1979, streamflow was too low to transport the second peak of material observed below the road construction site downstream to the main stream sampler. This was the lowest runoff year observed for these streams. In 1980, samples taken below the road construction site still showed some elevated values (maximum of 30.0 mg/L and 3.4 Nephlometric Turbidity Units (NTU)), but sediment and turbidity were decreasing to near background values. The main stream site, however, showed elevated suspended sediment values through May, with values as high as 74.0 mg/L; this was at about the peak flow. Apparently, material was deposited in the nearly 2.5 km of stream channel between the road construction site and the main stream site--awaiting the high flows of 1980 to be transported. By 1981, all sites were again near background values.

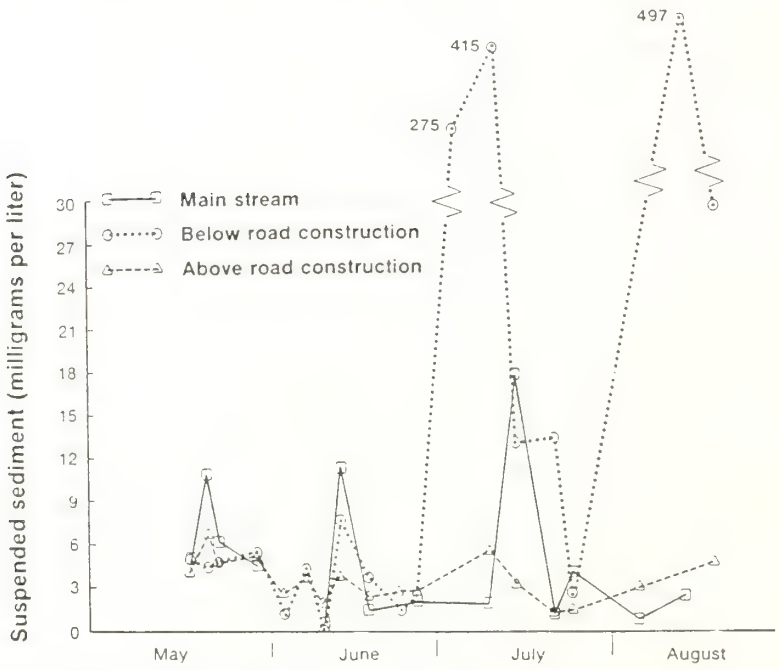


Figure 7--Suspended sediment chronology from three locations in Hansel Creek, 1979.

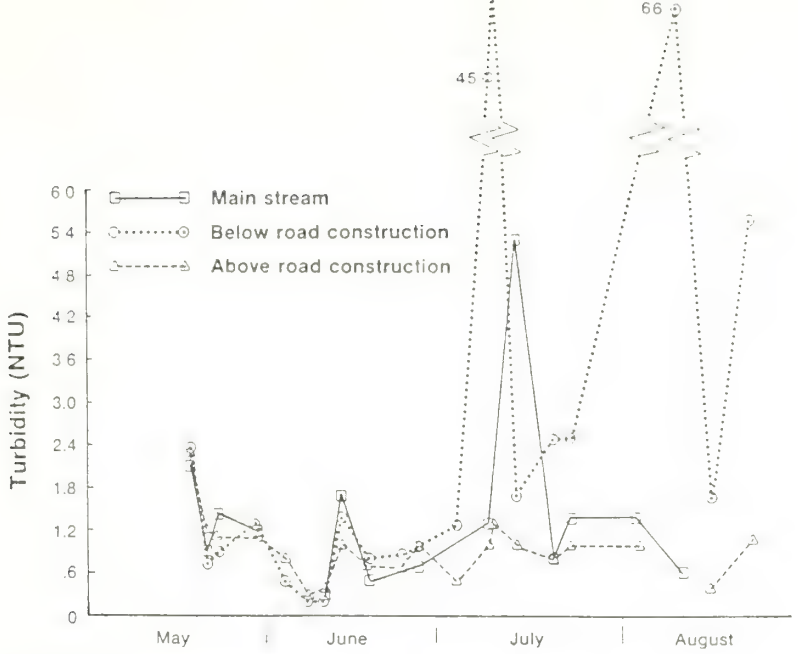


Figure 8--Turbidity chronology from three locations in Hansel Creek, 1979.

Conclusions

In this case study, chemical output from these high elevation, snow-zone watersheds was relatively insensitive to timber harvest. Elevated nitrate outputs have been shown in some clearcutting studies, but in others the response has been small or has not been observed. Clearcutting only portions of watersheds apparently reduced the harvest impact on all nutrient output. The mechanisms of nutrient losses are complicated and influenced by depressed or excessive precipitation. The effects of abnormal climatic events in years before and during this study could not be determined. Nitrate output may have decreased because decomposers immobilized nitrogen in the downed timber that remained onsite for 2 years. Stream turbidity and sediment production increased with road construction but declined rapidly to nearly background levels within 2 years.

Air and water temperatures generally increased with increased site exposure. The anomaly of decreased maximum and minimum temperatures after timber harvest in one stream emphasizes how quickly local conditions may influence thermal conditions in these low-volume streams.

The logging practices used on the Hansel Creek area were effective in protecting the water resource from unacceptable damage. Incomplete streamflow records prevented a rigorous test for changes in water yield after timber harvest. We are convinced, however, from the available records that yield increases were small and hydrologically unimportant. Logging methods and cutting percentages used here should adequately protect the water resource in similar areas of the eastern Cascade Range.

English Equivalents

To convert	To	Multiply by:
milligram (mg)	ounces	0.00003527
milligrams per liter (mg/L)	parts per million	1.0
gram (g)	ounces	0.03527
grams per hectare (g/ha)	pounds per acre	0.0008927
hectare (ha)	acre	2.471
centimeter (cm)	inches	0.3937
meter (m)	feet	3.281
kilometer (km)	miles	0.6214
cubic meter (m^3)	cubic feet	35.31
liter (L)	gallon	0.2642
liters per second (L/s)	cubic feet per second	0.03531
Celsius	Fahrenheit	(9/5 °C) + 32

Literature Cited

Chapman, H.D.; Pratt, P.F. 1961. Methods of analysis for soils, plants and waters. Riverside, CA: University of California, Division of Agricultural Science. 309 p.

Golterman, H.L.; Clymo, R.S. 1969. Methods for chemical analysis of fresh water. Int. Biol. Program Handb. 8. Oxford and Edinburgh: Blackwell Scientific Publications. 172 p.

Helvey, J.D.; Fowler, W.B.; Klock, G.O.; Tiedemann, A.R. 1976a. Climate and hydrology of the Entiat Experimental Forest watersheds under virgin cover. Gen. Tech. Rep. PNW-42. Portland, OR. U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 18 p.

Helvey, J.D.; Tiedemann, A.R.; Fowler, W.B. 1976b. Some climatic and hydrologic effects of wildfire in Washington State. In: Proceedings, 15th Annual Tall Timbers Fire Ecology Conference; 1974 October 15-16; Portland, OR. Tallahassee, FL: Tall Timbers Research Station. 15: 201-222.

Holtan, H.N.; Minshall, N.E.; Harrold, L.L. 1962. Field manual for research in agricultural hydrology. Agric. Handb. 224. Washington, DC: U.S. Department of Agriculture, Soil and Water Division, Agricultural Research Service. 215 p.

Martin, C. Wayne; Noel, Diane S.; Federer, C. Anthony. 1984. Effects of forest clearcutting in New England on stream chemistry. Journal of Environmental Quality. 13(2): 204-210.

McColley, P.D. 1976. Soil resource inventory, Wenatchee National Forest. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 318 p.

Robinson, J.W. 1966. Atomic absorption spectroscopy. New York: Marcel Dekker. 204 p.

Tiedemann, A.R.; Helvey, J.D.; Anderson, T.D. 1978. Stream chemistry and watershed nutrient economy following wildfire and erosion control fertilization in eastern Washington. Journal of Environmental Quality. 7(4): 580-588.

Vitovsek, Peter M.; Melillo, Jerry M. 1979. Nitrate losses from disturbed forests: patterns and mechanisms. Forest Science. 25(4): 605-619.

Wood, E.D.; Armstrong, F.A.J.; Richards, F.A. 1967. Determination of nitrate in seawater by calcium-copper reduction to nitrate. Journal of Marine Biological Association. 47: 23-31.

GPO 592-278/80050

Fowler, W.B.; Anderson, T.D.; Helvey, J.D. 1988. Changes in water quality and climate after forest harvest in central Washington State. Res. Pap. PNW-RP-388. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 12 p.

Chemical output of nitrate, calcium, magnesium, sodium, potassium, and organic nitrogen were determined on a grams-per-hectare-per-day basis for five treatment watersheds and a control watershed. Water samples were collected from April to October during 3 pretreatment and 3 posttreatment years (1978 to 1983). Except for increased calcium and sodium in several streams, regression equations comparing treatment with control showed no significant difference for pretreatment and posttreatment output. Output generally declined in the posttreatment years. Cyclic changes in output from these and other streams in the eastern Cascade Range in Washington appeared to occur regardless of treatment and were probably related to precipitation. Mean maximum air temperature increased during the posttreatment period in all the small watersheds, but stream temperatures were relatively unaffected.

Keywords: Water quality, sediment production, temperature, logging effects, Washington.

The **Forest Service** of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing Nation.

The U.S. Department of Agriculture is an Equal Opportunity Employer. Applicants for all Department programs will be given equal consideration without regard to age, race, color, sex, religion, or national origin.

Pacific Northwest Research Station
319 S.W. Pine St.
P.O. Box 3890
Portland, Oregon 97208

January 1988

U.S. Department of Agriculture
Pacific Northwest Research Station
319 S.W. Pine Street
P.O. Box 3890
Portland, Oregon 97208

BULK RATE
POSTAGE +
FEES PAID
USDA-FS
PERMIT No. G-40

Official Business
Penalty for Private Use, $300

do NOT detach label

United States
Department of
Agriculture

Forest Service

Pacific Northwest
Research Station

Research Paper
PNW-RP-389

TEXAS' Forest Products Industry: Performance and Contribution to the State's Economy, 1970 to 1980

Con H Schallau, Wilbur R. Maki, Bennett B. Foster, and Clair H. Redmond

Abbreviations

States

AL	Alabama
AR	Arkansas
FL	Florida
GA	Georgia
KY	Kentucky
LA	Louisiana
MS	Mississippi
NC	North Carolina
OK	Oklahoma
SC	South Carolina
TN	Tennessee
TX	Texas
VA	Virginia
SO	South
US	United States

Industries

FPI	Forest Products Industry
LWP	Lumber and Wood Products
PAP	Paper and Allied Products
WF	Wood Furniture

Authors

CON H SCHALLAU is a research economist at the Pacific Northwest Research Station, Forestry Sciences Laboratory, 3200 Jefferson Way, Corvallis, Oregon 97331. WILBUR R. MAKI is a professor, University of Minnesota, Department of Agricultural and Applied Economics, St. Paul, Minnesota 55108. BENNETT B. FOSTER and CLAIR H. REDMOND are, respectively, forest economist and economist, USDA Forest Service, Southern Region, State and Private Forestry, 1720 Peachtree Road N.W., Atlanta, Georgia 30367.

Abstract

Schallau, Con H; Maki, Wilbur R.; Foster, Bennett B.; Redmond, Clair H. 1987. Texas' forest products industry: performance and contribution to the State's economy, 1970 to 1980. Res. Pap. PNW-RP-389. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 22 p.

Even though Texas consumes more forest products than it produces, its forest products industry has a conspicuous record. Between 1970 and 1980, employment in the forest products industry increased by 12,000. Only one Southern State, North Carolina, showed a larger absolute gain. Texas was also second to North Carolina in improving its comparative advantage during the 1970's. In 1977, it ranked fourth among the 13 Southern States in value added, but first in growth of value added.

Keywords: Forest products industries, economics (forest products industries), employment (forest products industries), Texas.

Preface

This report briefly describes Texas' forest products industry—its composition, location, evolution, and relation to economic activity elsewhere in the State, the South, and the Nation.

This is one in a series of reports for each of the 13 Southern States. These reports are companions to an analysis of the interregional competition in the forest products industries of the South and the Pacific Northwest.

Estimates of employment and earnings shown in this report were derived from U.S. Department of Commerce data. All references to dollar amounts are in constant 1977 dollars.

Highlights

Throughout the 1970's, Texas' forest products industry exhibited phenomenal growth by many measures.

- Twelve thousand new jobs were created in the industry (a 25-percent increase). Had the growth been the same as for the Nation, the State's forest products industry would have had 10,000 fewer new jobs. Only North Carolina added more jobs, and only Oklahoma had greater proportional growth.

- The forest products industry is composed of paper and allied products, lumber and wood products, and wood furniture manufacturing. Employment in the lumber and wood products segment grew fastest —a 62-percent increase.

- The value added by the forest products industry increased 38 percent between 1972 and 1977. Lumber and wood products exhibited the most growth. Value added by manufacturing totaled $400 million in 1977—fourth highest in the South.

- Productivity (measured as value added minus payroll) grew more rapidly in Texas than for the South as a whole. This growth was second only to Alabama's and means that Texas has become more efficient and more competitive.

- In 1980, the Texas forest products industry did not qualify as an economic base (or basic) industry, indicating that Texas was not self-sufficient in forest products; imports exceeded exports. This means the industry did not drive the economy by bringing in new dollars from outside markets.

- In some sub-State areas, the forest products industry does qualify as basic. The Nacogdoches area, including 12 surrounding counties, was the most timber-dependent region of the State, and accounted for 15 percent of the State's employment in the forest products industry.

- The importance of the forest products industry is concealed because a significant segment of secondary processing activity is located in the highly urbanized Houston-Beaumont and Dallas-Fort Worth areas.

- In increased shares of both employment and earnings, Texas was second only to North Carolina in improving its comparative advantage during the 1970's.

Contents

1 **The Forest Products Economy of Texas**
1 The Work Force
2 Components of the State's Economic Base
4 Geographical Importance of the Forest Products Industry
5 Composition of the Forest Products Industry
6 Average Annual Earnings per Worker
7 Value Added by the Forest Products Industry
8 Capital Productivity
9 **The Forest Products Industry in the South**
9 Importance of the Industry Across the South
10 Industry Composition
12 Growth of Employment
13 Average Annual Earnings
14 Shift in Employment and Earnings
16 Value Added by the Forest Products Industry
17 Capital Productivity
18 **Acknowledgment**
18 **Appendix 1**
18 Tables
22 **Appendix 2**
22 Texas Counties by Sub-State Planning and Development Districts

The Forest Products Economy of Texas

The Work Force

Texas' estimated full- and part-time work force in 1980 was comprised of an estimated 6.94 million employees and proprietors (see table 1 for sources of employment and earnings data). Texas' work force grew significantly faster between 1970 and 1980 than did the national average (44.7 versus 22.3 percent). Total earnings—wage and salary payments and proprietorial income—grew much faster than the national average; measured in constant 1977 dollars, the State's earnings increased by 67.2 percent compared with 27.4 percent for the Nation. The following tabulation shows that services, manufacturing, retail trade, and State and local government were the State's four largest employer categories.

	Percent of total employment, 1980	
Employers	**Texas**	**U.S.**
Major industries:		
Services	16.2	18.2
Manufacturing (including the the forest products industry[1])	15.1	19.2
Retail trade	14.7	14.2
State and local government	11.8	12.6
Self-employed	6.7	6.6
Construction	6.1	4.1
Wholesale trade	6.0	5.0
Transportation	5.2	4.8
Agriculture	4.9	4.4
Finance, insurance, and real estate	4.8	5.0
Mining	3.4	1.0
Federal military	2.7	2.3
Federal civilian	2.4	2.8
Total[2]	100.0	100.0

[1] The forest products industry has three segments: (1) lumber and wood products (SIC 24), except mobile homes (SIC 2451); (2) wood furniture manufacturing (SIC 2511, 2512, 2517, 2521, 2541); and (3) paper and allied products (SIC 26).

[2] Sum of parts may not equal totals because of rounding.

Components of the Economic Base

Along with total employment, there is another and perhaps more important way to judge an industry's contribution to the economy of Texas. For the State's economy to grow and develop, it must attract new dollars so residents can buy goods and services produced elsewhere. The industries that export products and services beyond local boundaries (that is, to elsewhere in the State, to other States, and to the world) and bring in new dollars constitute the area's economic base. Generally speaking, most manufacturing employment is classified as economic base (or basic); service or residentiary employment (for example, barber shops, realty firms, schools, and local government) is geared primarily to producing for local needs. Some services may, however, be basic. The Federal military, for example, provides national defense for all the Nation's citizens, and taxpayers outside Texas provide the financial support; Federal military therefore is one of Texas' basic industries.

Residentiary employment is supported by the economic base. Money flowing in provides income for wage earners and entrepreneurs to spend on locally purchased goods and services. The economic growth of a region usually depends on the success of its economic base.

We used the excess employment technique to identify the industries that comprise Texas' (or a sub-State district's) economic base. This approach accepts the national distribution of employment among industries as a norm. Any industry with employment in excess of this norm is considered to be producing for markets outside the State (or sub-State district) and is part of Texas' economic base. The percentage of Texas' excess employment served as an indicator of the State's dependency on a particular industry for generating new dollars from outside the State (table 2 shows how excess employment and industry dependency indicators for Texas were calculated).

In 1980, eight industries accounted for 89.4 percent of the State's excess employment—that is, its economic base (see tabulation below). These same industries accounted for a significantly smaller share (74.3 percent) in 1970. This change reflects some rather large shifts in the shares of certain industries. In 1970, agriculture and Federal military accounted for 25 percent of the State's basic employment; by 1980, they accounted for only 11.6 percent. The declining importance of the Federal military segment coincided with the cessation of the Nation's military involvement in Vietnam. At the same time, the oil and gas extraction and construction components of the economic base increased in importance, reflecting the rapid expansion of domestic oil production during the 1970's. More recently, OPEC (Organization of Petroleum Exporting Countries) oil prices have declined, and domestic exploration for and production of oil have declined significantly in Texas. The relative importance of the various components of the State's economic base have been altered since 1980.

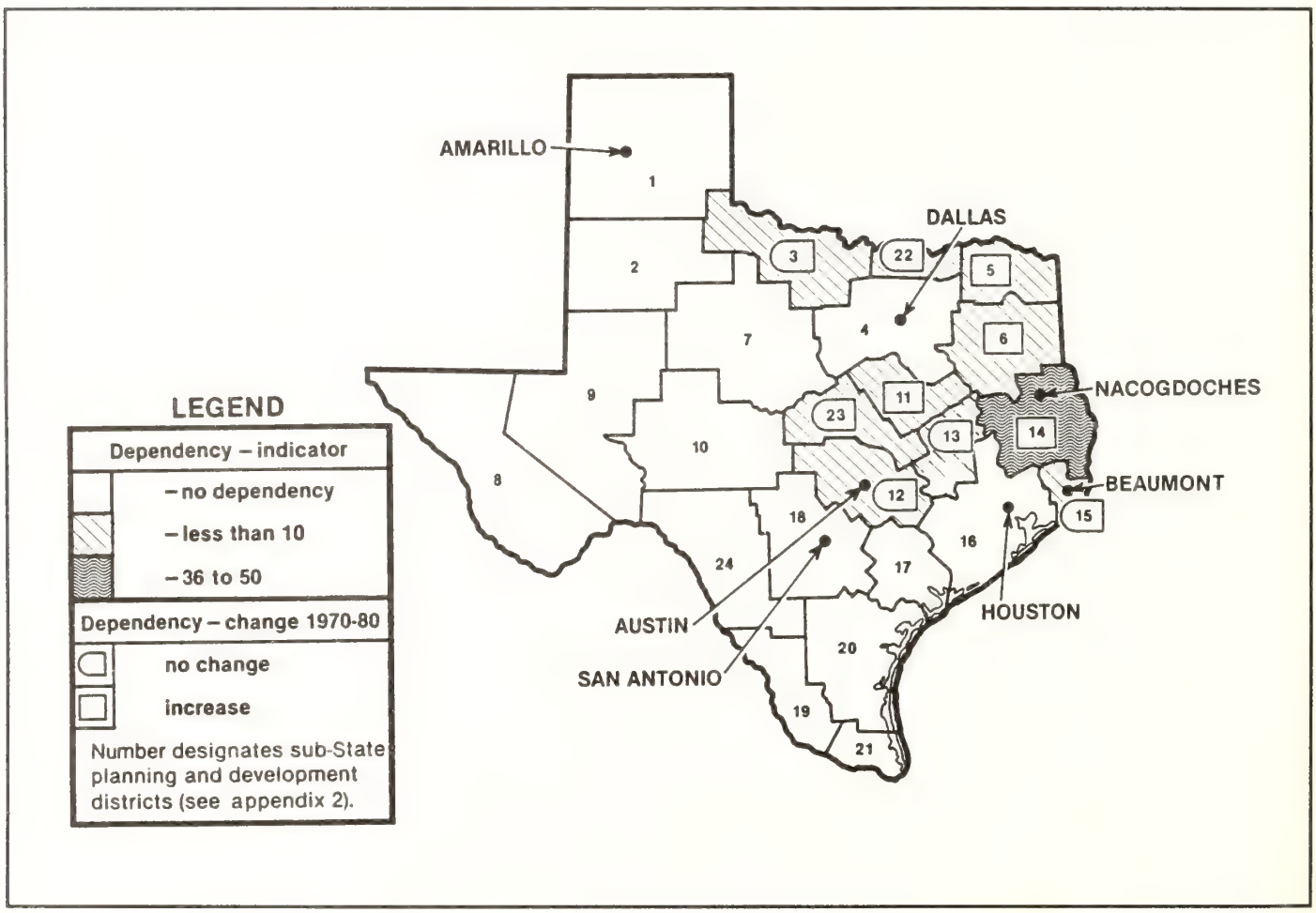
Both wholesale trade and retail trade qualify as basic industries; this is unusual and reflects Texas' role as one of the South's major regional trade centers.

The forest products industry does not qualify as a basic industry at the State level; but in some Sub-state localities, it accounts for a significant proportion of basic activities.

Economic base industries	Dependency indicator	
	1970	1980
	(Percent of economic base)	
Oil and gas extraction	17.6	31.6
Construction	8.7	22.5
Wholesale trade	10.4	11.8
Agriculture	12.0	7.2
Retail trade	4.6	5.1
Federal military	13.0	4.4
Petroleum refining	5.9	4.3
Electrical, gas, and sanitation services	2.1	2.5
Subtotal	74.3	89.4
All other basic industries	25.7	10.6
Total	100.0	100.0

Geographical Importance of the Forest Products Industry

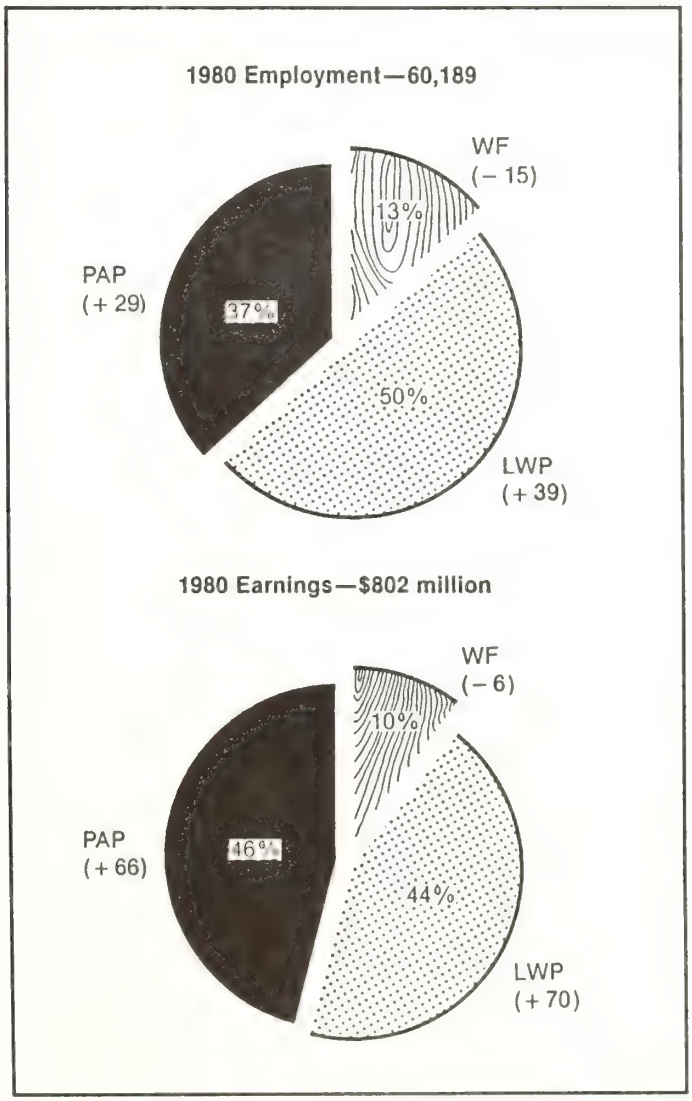
The contribution of the forest products industry to Texas' economic base varies considerably between sub-State districts (see appendix 2 for a list of counties by district). Of major significance is the concentration of secondary processing facilities (that is, those producing millwork, pallets, structural wood members, and converted paper and paperboard products) around the Dallas-Fort Worth and Houston-Beaumont urban areas. Although their respective forest products industries do not qualify as basic—and, therefore, are concealed—these areas account for over 40 percent of the State's employment in the forest products industry. Primary-processing operations for southern pine lumber, veneer, and plywood are concentrated in eastern Texas. The subdistrict area centered at Nacogdoches accounts for about 15 percent of the State's employment in the forest products industry.



Source: Sub-State estimates for 1970 and 1980 were derived from unpublished county data series provided by the U.S. Department of Commerce, Regional Economic Information System, Washington, DC, and from the Department's *County Business Patterns*. The numbers designate sub-State districts corresponding to the geographical classification of counties as shown in appendix 2.

Composition of the Forest Products Industry

Texas' forest products industry is comprised of paper and allied products, lumber and wood products (not including mobile homes), and wood furniture manufacturing. Employment decreased in the wood furniture segment between 1970 and 1980 and increased in the other two segments. The growth in employment in the lumber and wood products segment is particularly noteworthy because, while the southern pine plywood industry experienced a shakeout[3] during the 1970's, solid-wood manufacturing continued to increase.



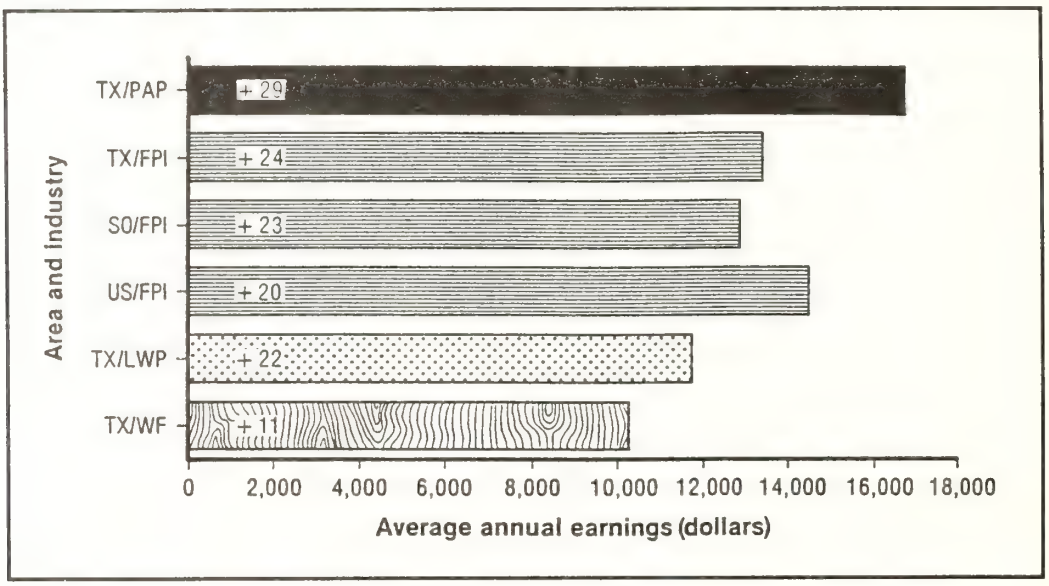
Numbers in parentheses show percentage of change from 1970 to 1980.

[3] Shakeout is one of five fundamental stages of product-market development evolution: development, growth, shakeout, maturity-saturation, and decline. See, Cleaves, David A.; O'Laughlin, Jay. 1985. Forest inventory, plant location and company strategies. In: Proceedings of the 1985 Southern forest economic workers (SOFEW) workshop; 1985 March 13-15; Athens, GA. Athens GA: University of Georgia: 35-43.

Average Annual Earnings per Worker

Average annual 1980 earnings per worker in paper and allied products were greater than were earnings in the other two segments of the forest products industry. Higher average skill levels, capital investment per worker, and unions account for this difference. Earnings in the wood furniture industry were less than 60 percent of those for paper and allied products and were significantly below the average for all forest products industries in the South and the United States.

The rate of growth in average earnings was greater for Texas' forest products industry than for the South and the Nation. The difference resulted from the growth in earnings of the paper and allied products segment. The rate of change for wood furniture was considerably less than that of the Nation and the South.

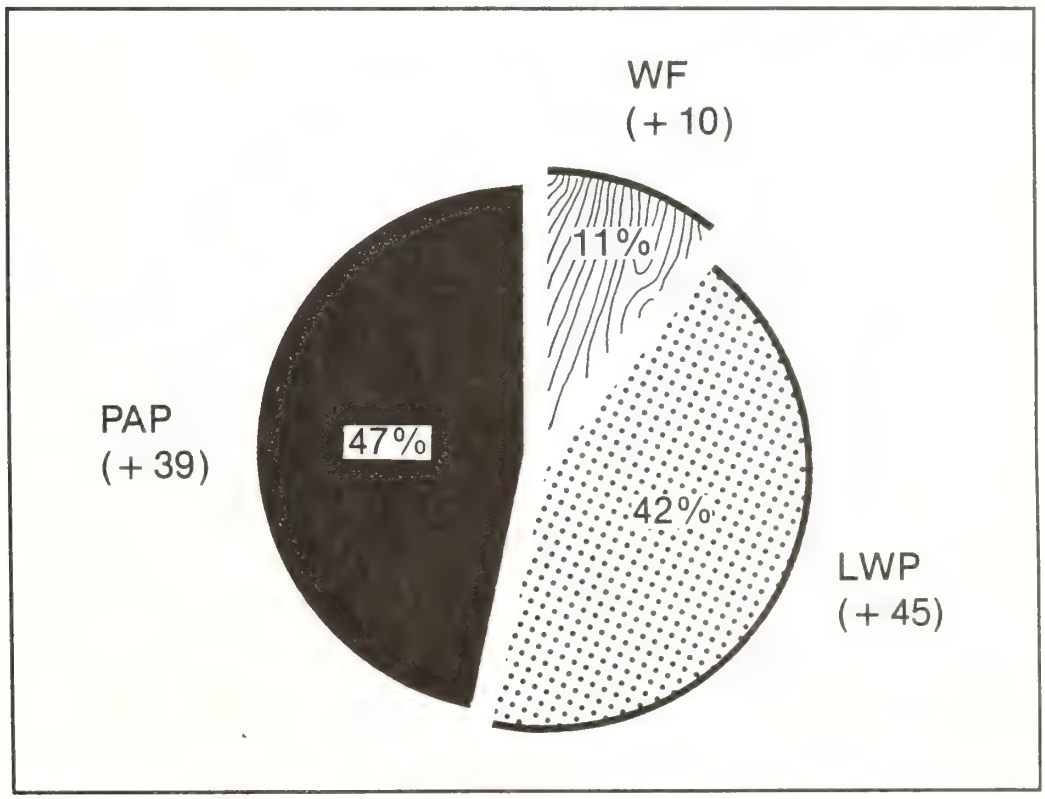


Numbers in bars show percentage of change from 1970 to 1980.

Value Added by the Forest Products Industry

Value added by manufacturing represents income payments made directly to workers and business owners. It is equal to the value of shipments less the cost of materials, parts, supplies, fuel, goods purchased for retail, electric energy, and contract work. Value of shipments includes goods and services provided by other industries; value added includes only the economic contributions of the State's manufacturing industries. Value added by manufacturing is therefore considered a better monetary gauge of the relative economic importance of a manufacturing industry. In 1977, paper and allied products had the largest share of the $1.4 billion of value added by Texas' forest products industry.

In addition to the forest products industry experiencing above-average growth in employment, value added by the industry increased substantially between 1972 and 1977. Total value added increased by 38 percent; lumber and wood products experienced the most growth and wood furniture the least.



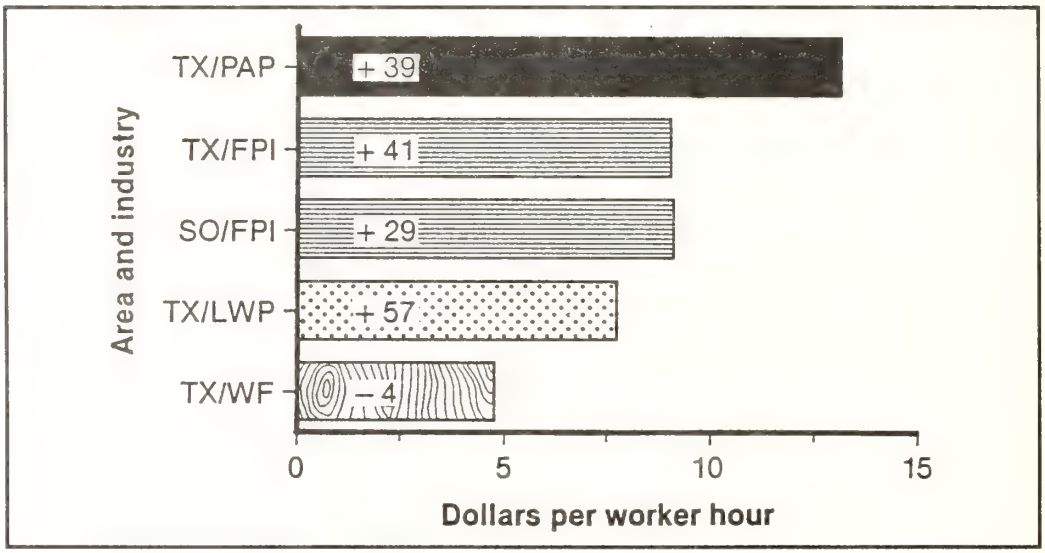
Numbers in parentheses show percentage of change from 1972 to 1977.

Capital Productivity

Increases in productivity are necessary for an industry to remain competitive in the marketplace. Productivity of an industry is measured in terms of value added minus payrolls per worker hour—VAMP (see table 3 for an explanation of how productivity was calculated for Texas' forest products industry). This measure of productivity represents profits before taxes and adjusts for wide differences in payroll among industries.

Paper and allied products had, by far, the highest productivity in Texas' forest products industry. Productivity per worker hour was almost 45 percent greater than the average for the State's forest products industry.

The lumber and wood products segment experienced the largest gain in productivity between 1972 and 1977. Paper and allied products is more capital intensive and, in the past, has attracted considerable investment in new facilities and equipment. During the mid-1970's, its productivity increased despite increased labor costs. This segment exhibited a larger gain in productivity than was average for the South.

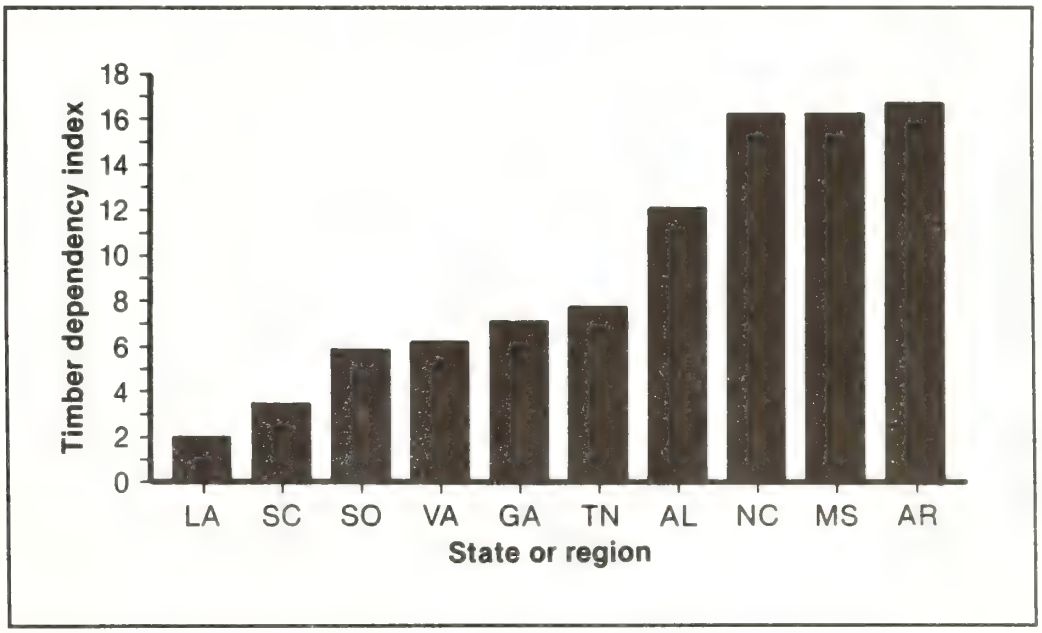


Numbers in bars show percentage of change from 1972 to 1977.

The Forest Products Industry in the South

Importance of the Industry Across the South

The dependency indicators suggest that in 1980 all but four States in the South manufactured forest products in excess of statewide needs. Florida, Kentucky, Oklahoma, and Texas were not self-sufficient in forest products; these States imported more forest products than they exported, so their respective forest products industries did not generate new dollars from the outside. In three States—Arkansas, Mississippi, and North Carolina—the forest products industry accounted for about one of six basic employees.

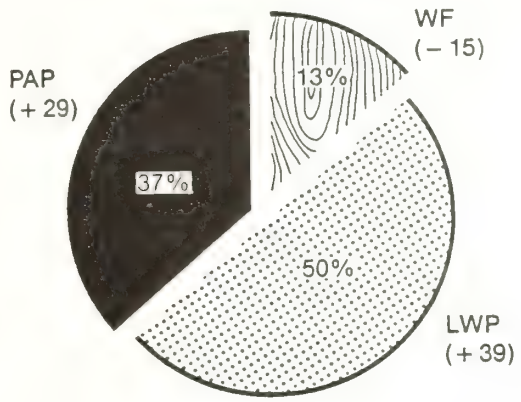


Industry Composition

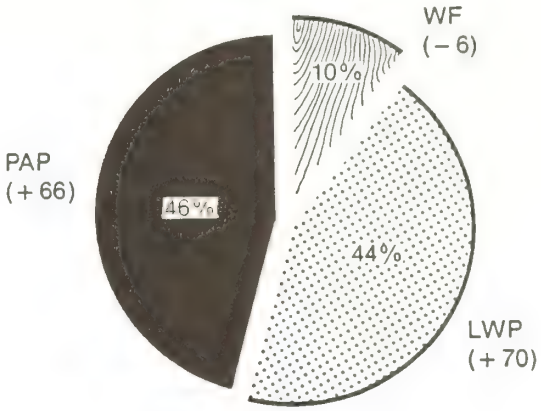
Both the paper and allied products and the lumber and wood product segments accounted for larger shares of 1980 employment and earnings in Texas' forest products industry than they did for the South. During the 1970's, employment in these two segments increased at a much faster rate in Texas than for the South. Employment in the wood furniture segment is much less prominent in Texas and the Nation than in the South in general; earnings and employment in wood furniture declined in Texas while they increased in the South and the Nation.

TEXAS

1980 Employment—60,189

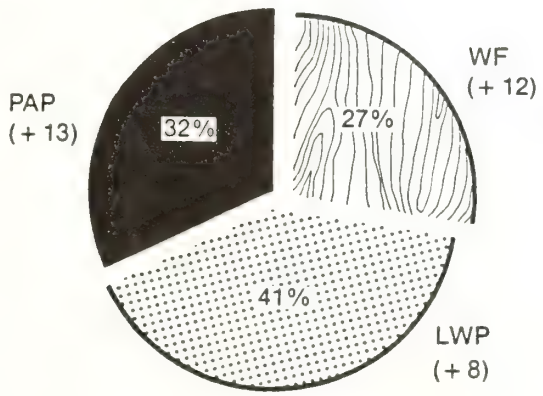


1980 Earnings—$802 million

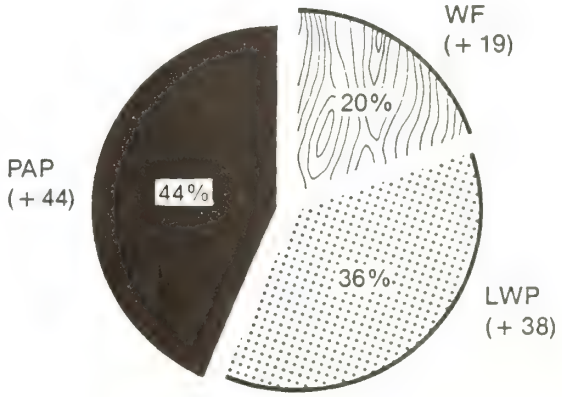


THE SOUTH

1980 Employment—620,567

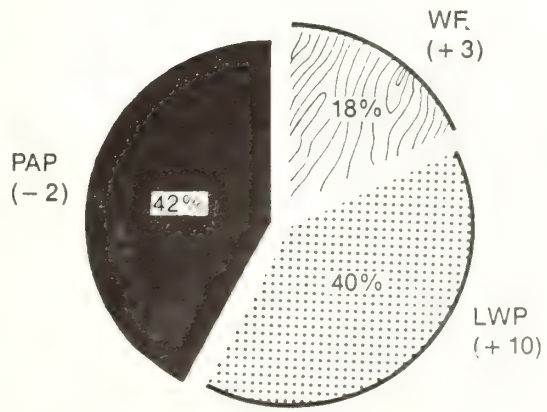


1980 Earnings—$7.96 billion

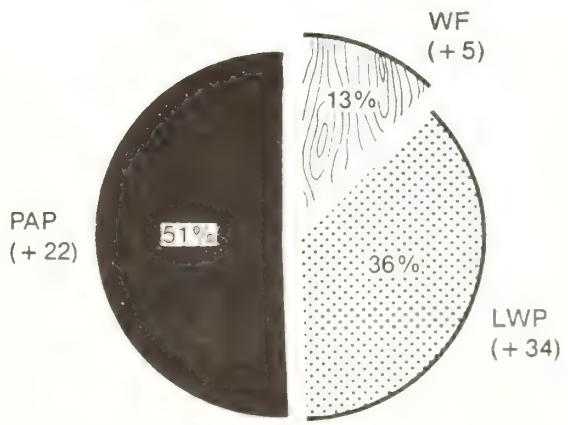


UNITED STATES

1980 Employment—1,634,000



1980 Earnings—$23.65 billion

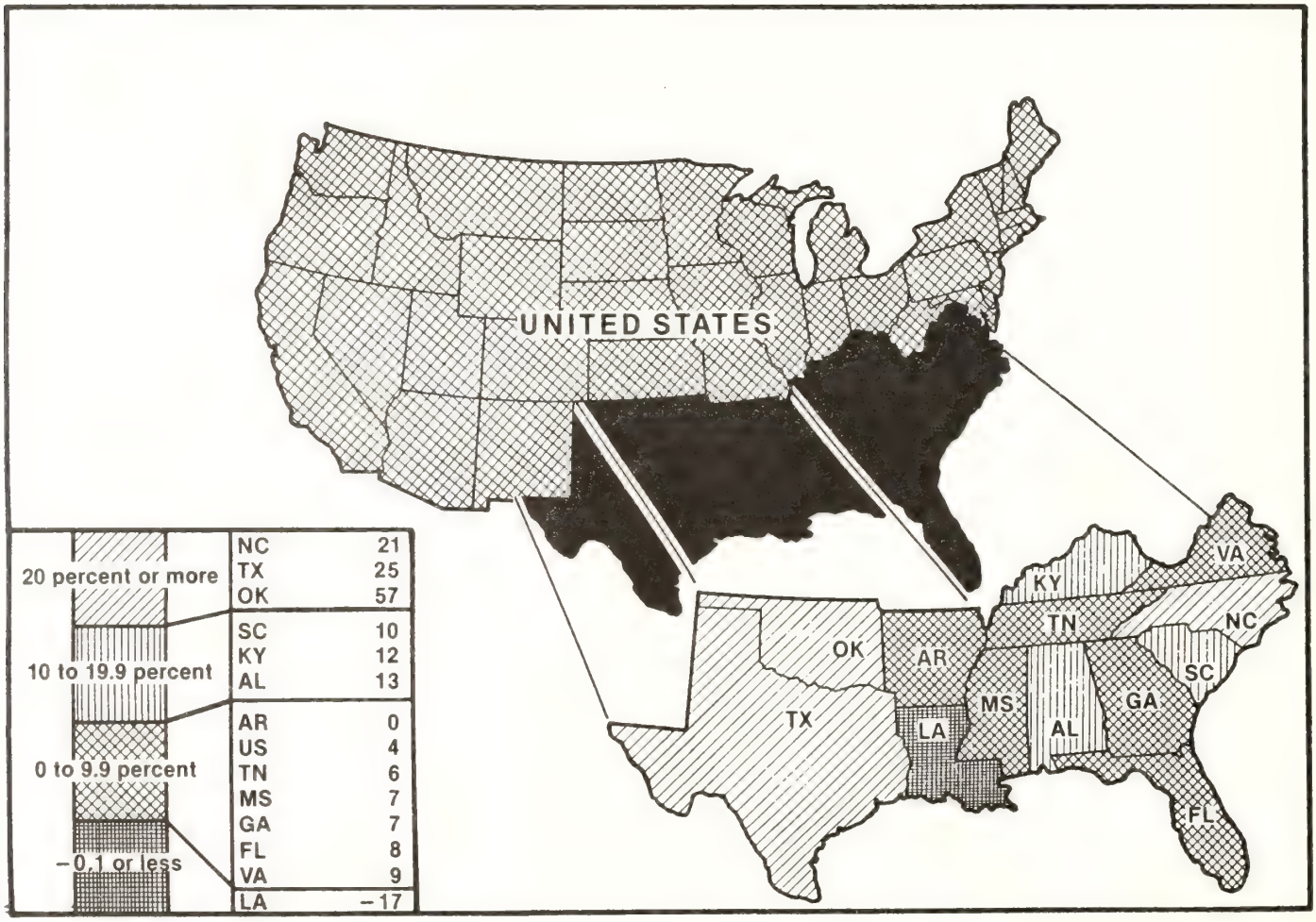


Numbers in parentheses show percentage of change from 1970 to 1980.

Growth of Employment

Between 1970 and 1980, employment in the forest products industry in Texas increased by more than 12,000. Only one Southern State, North Carolina, exhibited a larger absolute gain. Oklahoma had a larger relative change, but in absolute terms, Texas surpassed it by a wide margin.

Employment in the forest products industry in each of the Southern States except Arkansas and Louisiana grew faster than did the U.S. counterpart. Between 1970 and 1980, employment in Oklahoma and Texas grew faster than the all-industry average of 22.3 percent.

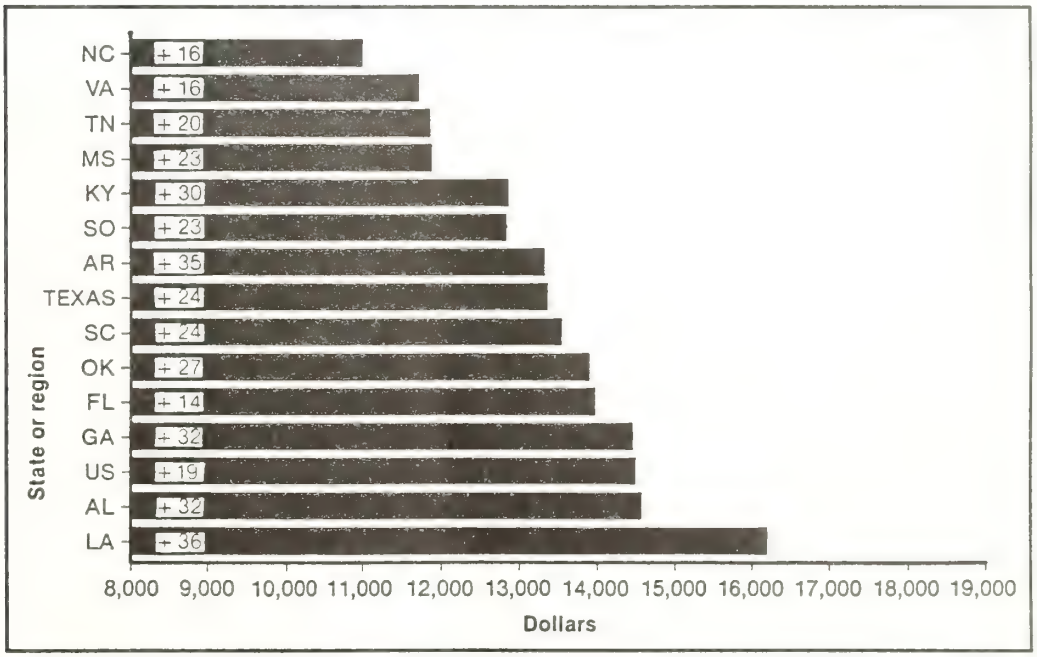


Average Annual Earnings

Average annual earnings per worker in the forest products industry differed significantly by State in 1980. About $5,000 separated the State with the highest (Louisiana) from the State with the lowest (North Carolina). Pulp and allied products manufacturing, which has traditionally paid higher wages than have other segments of the forest products industry, dominated Louisiana's forest products industry. Wood furniture, which has paid lower average wages, dominated North Carolina's industry.

Average annual forest products industry earnings in Texas were slightly above the average for all States in the South but below the average for the United States. Furthermore, earnings increased faster in Texas than in either the South or the Nation.

Generally speaking, paper and allied products dominated the forest products industry in the States with the highest average annual earnings. This relation reflects higher job skills and unions in pulp and paper manufacturing. Wages, by and large, were the lowest in States where the labor-intensive wood furniture industry was more important



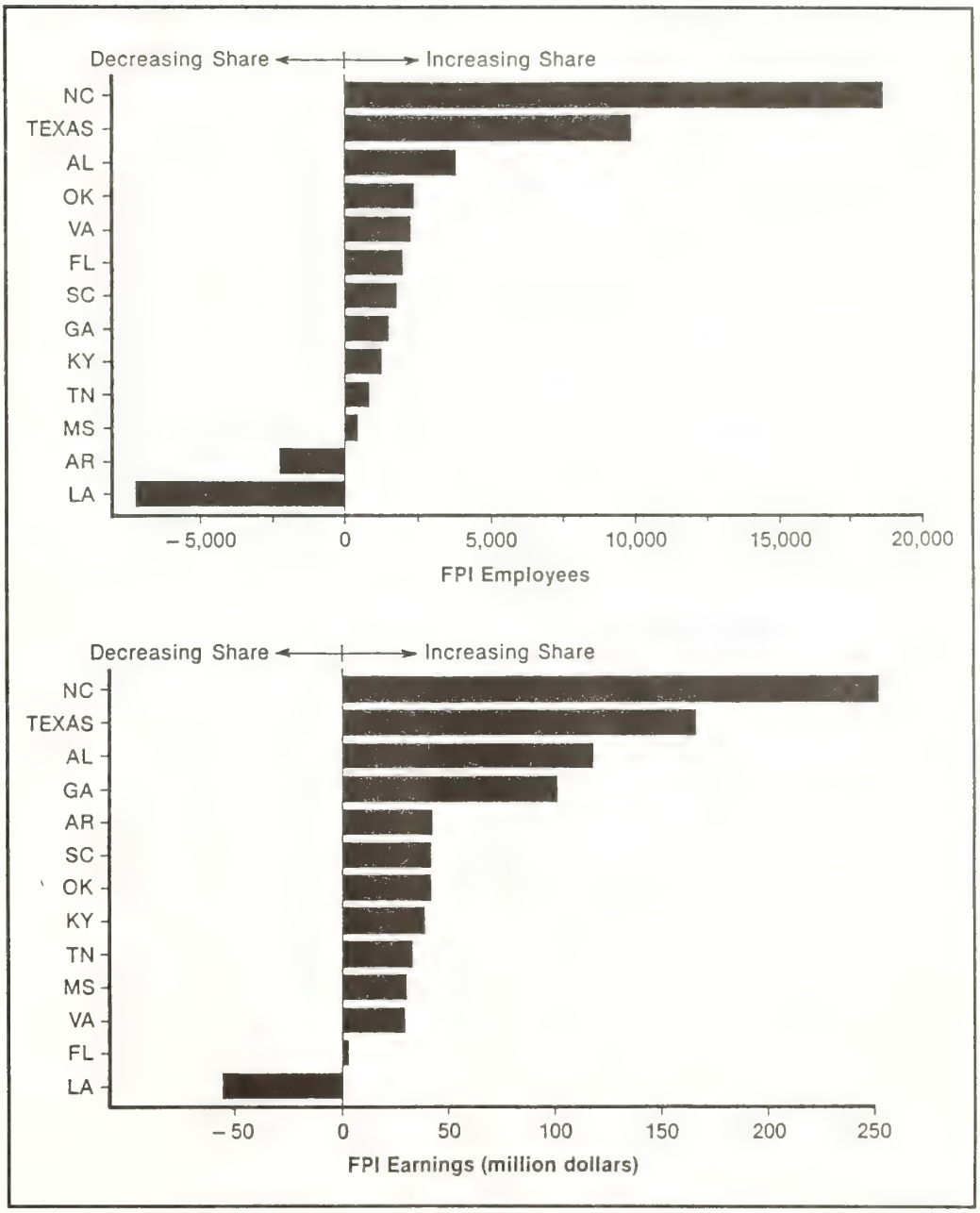
Numbers in bars show percentage of change from 1970 to 1980.

Shift in Employment and Earnings

The regional shift shows how much more or less employment and earnings a State would have had in the forest products industry in 1980 had it grown at the national rate. For example, Texas had nearly 10,000 more employees in 1980 than it would have had if its forest products industry had grown at the national rate.

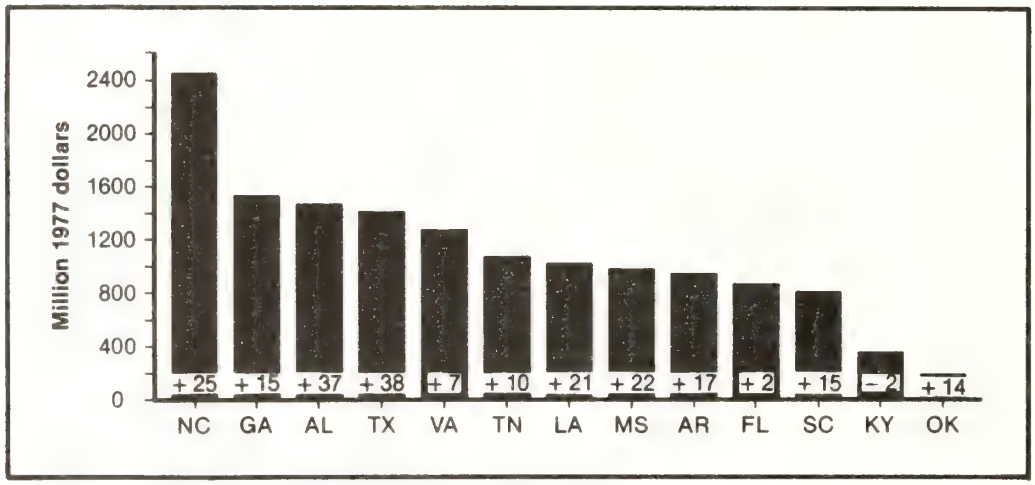
Between 1970 and 1980, total employment in the forest products industry remained constant. With the exception of Louisiana, it increased in every Southern State. All but Arkansas and Louisiana increased their share of the Nation's forest products industry employment, and all but Louisiana increased their share of earnings.

Increased shares of employment and earnings reflect the comparative advantage the South's forest products industry enjoyed over this industry in the rest of the Nation. Several factors (for example, relatively lower labor costs, lower raw materials costs, and closer proximity to markets) might account for a region's comparative advantage, although adverse trends in one factor need not reduce a region's advantage. In the South, increasing labor costs need not adversely affect a comparative advantage if those costs are offset by increased capital or labor productivity. For increased shares of both employment and earnings, Texas was second only to North Carolina in improving its comparative advantage during the 1970's.


Decreasing Share
Increasing Share
NC
TEXAS
AL
OK
VA
FL
SC
GA
KY
TN
MS
AR
LA
– 5,000
0
5,000
10,000
15,000
20,000
FPI Employees
Decreasing Share
Increasing Share
NC
TEXAS
AL
GA
AR
SC
OK
KY
TN
MS
VA
FL
LA
– 50
0
50
100
150
200
250
FPI Earnings (million dollars)

Value Added by the Forest Products Industry

In 1977, the forest products industry of North Carolina produced more value added than any other State in the South. Georgia was second among the 13 Southern States; Texas was fourth. One state, Kentucky, produced less value added in 1977 than in 1972. This can be attributed to a decline in secondary processing activities during the 1970's.



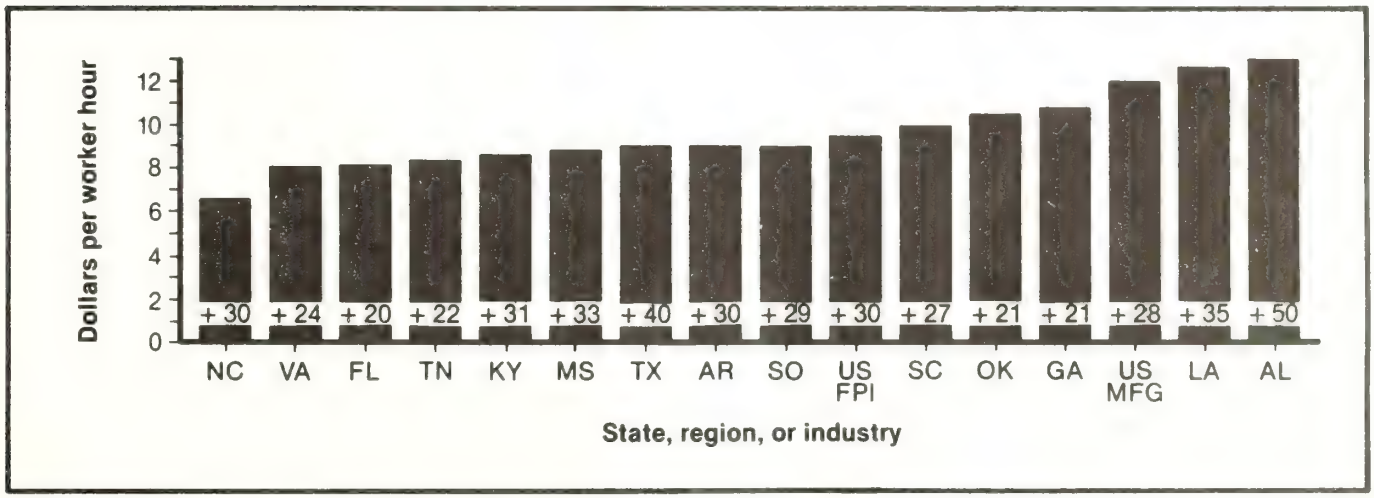
Numbers in bars show percentage of change from 1972 to 1977.

Capital Productivity

The paper and allied products segment, which is more capital-intensive and therefore more susceptible to technological change than are other segments of the forest products industry, exhibited the highest productivity within the forest products industry. Wood furniture, on the other hand, is the most labor-intensive of the three. North Carolina, for example, produced more value added than any other State in the South, but the productivity of its forest products industry in 1977 was the lowest, reflecting the dominant role of labor-intensive wood furniture manufacturing in North Carolina.

Increases in productivity exceeded increases in payroll per worker between 1972 and 1977 for all Southern States. This relation is partly responsible for the South's comparative advantage in the forest products industry.

In 1977, productivity of Texas' forest products industry was equal to the average for the 13 Southern States, but it was second only to Alabama in growth in productivity. This increase was achieved despite Texas' average annual wages being higher and growing faster than the average for the South.



Numbers in bars show percentage of change from 1972 to 1977.

Acknowledgment

Many helpful suggestions of several reviewers were incorporated in this research paper. This project was partially funded by the USDA Forest Service Resource Program and Assessment Staff, State and Private Forestry, Area Planning and Development, State Planning for Forest Resources.

Appendix 1

Tables

Table 1—Total labor and proprietorial employment and income, by industry, Texas, 1980[1]

Industry number	Industry	Employees	Total income
		Number	*Thousand 1977 dollars[2]*
Wage and salary			
1	Agriculture	78,088	1,658,508
2	Agricultural services, forestry, and fisheries	52,074	393,764
3	Coal mining	651	16,977
4	Oil and gas extraction	228,984	5,089,383
5	Metal mining	1,245	21,145
6	Nonmetallic minerals	7,680	133,099
7	Construction	421,277	6,757,065
8	Food and kindred products	97,644	1,276,362
9	Tobacco	108	1,063
10	Textile mill production	5,753	62,435
11	Apparel and other textiles	74,864	583,614
12	Paper and allied products	22,103	368,334
13	Printing and publishing	62,409	764,209
14	Chemical and allied products	80,807	1,844,186
15	Petroleum refining	39,595	1,297,743
16	Rubber and miscellaneous plastics	30,755	433,040
17	Leather and leather products	8,314	71,181
18	Lumber and wood products, excluding mobile homes	30,066	352,218
19	Mobile homes	5,873	68,801
20	Wood furniture	8,020	81,960
21	Other furniture and fixtures	8,726	89,175
22	Stone, clay, and glass products	44,359	651,694
23	Primary metals	47,387	965,442
24	Fabricated metals	97,619	1,519,595
25	Machinery, excluding electrical	159,566	2,727,133
26	Electrical machinery	108,404	1,665,125
27	Transportation equipment, excluding motor vehicles	67,551	1,333,016
28	Motor vehicles	13,855	238,847
29	Instruments and related equipment	20,464	276,722
30	Miscellaneous manufacturing	13,393	151,832
31	Railroad transportation	30,089	603,711
32	Trucking and warehousing	93,639	1,512,911
33	Local transit	7,978	99,012

See footnotes at end of table.

Table 1—Total labor and proprietorial employment and income, by industry, Texas, 1980[1] (continued)

Industry number	Industry	Employees	Total income
		Number	*Thousand 1977 dollars[2]*
Wage and salary			
34	Air transportation	36,078	820,863
35	Pipeline transportation	5,534	130,802
36	Transportation services	14,133	233,093
37	Water transportation	21,951	392,001
38	Communications	83,658	1,456,618
39	Electric, gas, and sanitation services	69,268	1,323,369
40	Wholesale trade	418,530	6,999,093
41	Retail trade	1,020,143	8,679,661
42	Banking	87,047	1,064,998
43	Other credit agencies	59,223	1,089,946
44	Insurance	108,433	1,692,142
45	Real estate and combinations	82,014	961,900
46	Hotel and other lodging	61,676	438,178
47	Personal, miscellaneous business, and repair services	288,988	3,444,467
48	Auto repair service	38,661	552,341
49	Amusement	34,330	267,682
50	Motion pictures	10,140	71,257
51	Private households	128,422	369,051
52	Medical and other health	283,488	4,003,239
53	Private education	44,771	384,086
54	Nonprofit organizations	131,876	872,984
55	Miscellaneous services	98,148	2,675,867
56	Federal civilian	165,759	2,601,596
57	Federal military	187,602	1,525,579
58	State and local government	814,919	7,774,690
Proprietorial			
59	Nonfarm proprietors	462,612	6,193,605
60	Farm proprietors	210,433	1,240,771
	Total	6,937,177	90,369,181

[1] Source of data for this table for Texas, other States of the South, and the United States: unpublished data, U.S. Department of Commerce,Regional Economics Measurements Division, Regional Economic Information System (REIS), Washington, DC, 1982. Unpublished data used by the U.S.Department of Commerce in preparing their County Business Patterns (CBP) series on employment and payroll were used to differentiate wood-related from nonwood-related employment and earnings. For example, CBP data were used to separate mobile homes (no. 19, above) from the lumber and wood products (no. 18) industry. Wood furniture (no. 20) was similarly separated from other furniture and fixtures (no. 21).

[2] The Personal Consumption Expenditure (CPE) deflator, 1977 = 100, was used to deflate nominal dollars.

Table 2—Calculation of 1980 dependency indexes for Texas

(In percent)

Industry	Employment		Texas excess employment[1]	Dependency index[2]
	Texas	United States		
Agriculture	1.30	1.46	—	—
Agricultural services, forestry, and fisheries	.87	.62	0.25	2.47
Farm proprietors	3.51	3.03	.48	4.73
Coal mining	.01	.27	—	—
Oil and gas extraction	3.82	.60	3.22	31.62
Metal mining	.02	.11	—	—
Nonmetallic minerals	.13	.14	—	—
Construction	7.03	4.74	2.28	22.47
Food and kindred products	1.63	1.87	—	—
Tobacco	—	.07	—	—
Textile mill production	.10	.93	—	—
Apparel and other textiles	1.25	1.39	—	—
Paper and allied products	.37	.76	—	—
Printing and publishing	1.04	1.37	—	—
Chemical and allied products	1.35	1.22	.13	1.28
Petroleum refining	.66	.22	.44	4.33
Rubber and miscellaneous plastics	.51	.80	—	—
Leather and leather products	.14	.26	—	—
Lumber and wood products, excluding mobile homes	.50	.71	—	—
Mobile homes	.10	.05	.05	.49
Wood furniture	.13	.32	—	—
Other furniture and fixtures	.15	.19	—	—
Stone, clay, and glass products	.74	.73	.01	.09
Primary metals	.79	1.26	—	—
Fabricated metals	1.63	1.77	—	—
Machinery, excluding electrical	2.66	2.73	—	—
Electrical machinery	1.81	2.31	—	—
Transportation equipment, exluding motor vehicles	1.13	1.21	—	—
Motor vehicles	.23	.87	—	—
Instruments and related equipment	.34	.77	—	—
Miscellaneous manufacturing	.22	.47	—	—
Railroad transportation	.50	.58	—	—
Trucking and warehousing	1.56	1.40	.16	1.59
Local transit	.13	.29	—	—
Air transportation	.60	.50	.10	1.02
Pipeline transportation	.09	.02	.07	.68
Transportation services	.24	.22	.01	.12
Water transportation	.37	.23	.14	1.34
Communications	1.40	1.48	—	—
Electric, gas, and sanitation services	1.16	.90	.25	2.48
Wholesale trade	6.98	5.79	1.20	11.77

See footnotes at end of table.

Table 2—Calculation of 1980 dependency indexes for Texas (continued)

(In percent)

Industry	Employment		Texas excess employment[1]	Dependency index[2]
	Texas	United States		
Retail trade	17.02	16.50	.52	5.10
Banking	1.45	1.72	—	—
Other credit agencies	.99	.99	—	—
Insurance	1.81	1.89	—	—
Real estate and combinations	1.37	1.16	.21	2.05
Hotel and other lodging	1.03	1.20	—	—
Personal, miscellaneous business, and repair services	4.82	4.69	.13	1.26
Auto repair service	.65	.63	.02	.15
Amusement	.57	.84	—	—
Motion pictures	.17	.24	—	—
Medical and other health	4.73	5.71	—	—
Private education	.75	1.47	—	—
Nonprofit organizations	2.20	3.01	—	—
Miscellaneous services	1.64	1.63	.01	.03
Federal civilian	2.77	3.27	—	—
Federal military	3.13	2.68	.45	4.42
Nonfarm proprietors	7.72	7.66	.06	.55
Total[3]	100.00	100.00	10.17	100.00

[1] Texas minus U.S. employment. Figures may not be exactly equal to Texas minus U.S. because of rounding. Dashes signify no excess employment.

[2] Individual industry excess employment expressed as a percentage of Texas' total excess employment (sum of column 4).

[3] Sum of parts may not equal totals because of rounding.

Table 3—Value added, hours worked, payroll, and capital productivity,[1] Texas forest products industry, 1977[2]

Industry	Value added	Payroll	Hours worked	Productivity	Productivity change, 1972-77
		-- $Million --	*Million*	*$VAMP per hour*	*Percent*
Lumber and wood products	600.4	248.9	46.0	7.64	+57.01
Wood furniture	150.6	80.0	15.0	4.71	-3.56
Paper and allied products	663.0	272.0	30.0	13.03	+39.45

[1] Productivity equals value added minus payroll (VAMP) divided by hours worked. For a discussion of VAMP, see W. Charles Sawyer and Joseph A. Ziegler. 1980. "The use of VAMP shift as a predictive model." Unpublished paper presented at the annual meeting of the Western Regional Science Association, Monterey, California

[2] Source: U.S. Bureau of the Census, Census of Manufactures, for 1972 and 1977, Texas and the United States, available in 1976 and 1980, respectively. In the few instances where data were not available for some subindustry segments, the distribution of the number of establishments was used to estimate nondisclosures.

Appendix 2

Texas Counties by Sub-State Planning and Development Districts

District code	Counties
1	Armstrong, Briscoe, Carson, Castro, Collingsworth, Dallam, Deaf Smith, Donley, Gray, Hall, Hansford, Hartley, Hemphill, Hutchinson, Lipscomb, Moore, Ochiltree, Oldham, Parmer, Potter, Randall, Roberts, Sherman, Swisher, Wheeler
2	Bailey, Cochran, Crosby, Dickens, Floyd, Garza, Hale, Hockley, King, Lamb, Lubbock, Lynn, Motley, Terry, Yoakum
3	Archer, Baylor, Childress, Clay, Cottle, Foard, Hardeman, Jack, Montague, Wichita, Wilbarger, Young
4	Collin, Dallas, Denton, Ellis, Erath, Hood, Hunt, Jonson, Kaufman, Navarro, Palo Pinto, Parker, Rockwall, Somervell, Tarrant, Wise
5	Bowie, Cass, Delta, Franklin, Hopkins, Lamar, Morris, Red River, Titus
6	Anderson, Camp, Cherokee, Gregg, Harrison, Henderson, Marion, Panola, Rains, Rusk, Smith, Upshur, Van Zandt, Wood
7	Brown, Callahan, Coleman, Comanche, Eastland, Fisher, Haskell, Jones, Kent, Knox, Mitchell, Nolam, Runnels, Scurry, Shackelford, Stephens, Stonewall, Taylor, Throckmorton
8	Brewster, Culberson, El Paso, Hudspeth, Jeff Davis, Presidio
9	Andrews, Borden, Crane, Dawson, Ector, Gaines, Glasscock, Howard, Loving, Martin, Midland, Pecos, Reeves, Terrell, Upton, Ward, Winkler
10	Coke, Concho, Crockett, Irion, Kimble, Mason, McCulloch, Menard, Reagan, Schleicher, Sterling, Sutton, Tom Green
11	Bosque, Falls, Freestone, Hill, Limestone, McLennan
12	Bastrop, Blanco, Burnet, Caldwell, Fayette, Hays, Lee, Llano, Travis, Williamson
13	Brazos, Burleson, Grimes, Leon, Madison, Robertson, Washington
14	Angelina, Houston, Jasper, Nacogdoches, Newton, Polk, Sabine, San Augustine, San Jacinto, Shelby, Trinity, Tyler
15	Hardin, Jefferson, Orange
16	Austin, Brazoria, Chambers, Colorado, Fort Bend, Galveston, Harris, Liberty, Matagorda, Montgomery, Walker, Waller, Wharton
17	Calhoun, De Witt, Goliad, Gonzales, Jackson, Lavaca, Victoria
18	Atascosa, Bandera, Bexar, Comal, Frio, Gillespie, Guadalupe, Karnes, Kendall, Kerr, Medina, Wilson
19	Jim Hogg, Starr, Webb, Zapata
20	Aransas, Bee, Brooks, Duval, Jim Wells, Kenedy, Kleburg, Live Oak, McMullen, Nueces, Refugio, San Patricio
21	Cameron, Hidalgo, Willacy
22	Cooke, Fannin, Grayson
23	Bell, Coryell, Hamilton, Lampasas, Milam, Mills, San Saba
24	Dimmit, Edwards, Kinney, La Salle, Maverick, Real, Uvalde, Val Verde, Zavala

Schallau, Con H; Maki, Wilbur R.; Foster, Bennett B.; Redmond, Clair H. 1987. Texas' forest products industry: performance and contribution to the State's economy, 1970 to 1980. Res. Pap. PNW-RP-389. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 22 p.

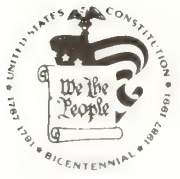
Even though Texas consumes more forest products than it produces, its forest products industry has a conspicuous record. Between 1970 and 1980, employment in the forest products industry increased by 12,000. Only one Southern State, North Carolina, showed a larger absolute gain. Texas was also second to North Carolina in improving its comparative advantage during the 1970's. In 1977, it ranked fourth among the 13 Southern States in value added, but first in growth of value added.

Keywords: Forest products industries, economics (forest products industries), employment (forest products industries), Texas.

The **Forest Service** of the U. S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives—as directed by Congress—to provide increasingly greater service to a growing nation.

The U.S. Department of Agriculture is an Equal Opportunity Employer. Applicants for all Department programs will be given equal consideration without regard to race, color, sex, religion, or national origin.

Pacific Northwest Research Station
319 S.W. Pine St.
P. O. Box 3890
Portland, Oregon 97208



December 1987

U.S. Department of Agriculture
Pacific Northwest Research Station
319 S.W. Pine Street
P.O. Box 3890
Portland, Oregon 97208

BULK RATE
POSTAGE +
FEES PAID
USDA-FS
PERMIT No. G-40

Official Business
Penalty for Private Use, $300

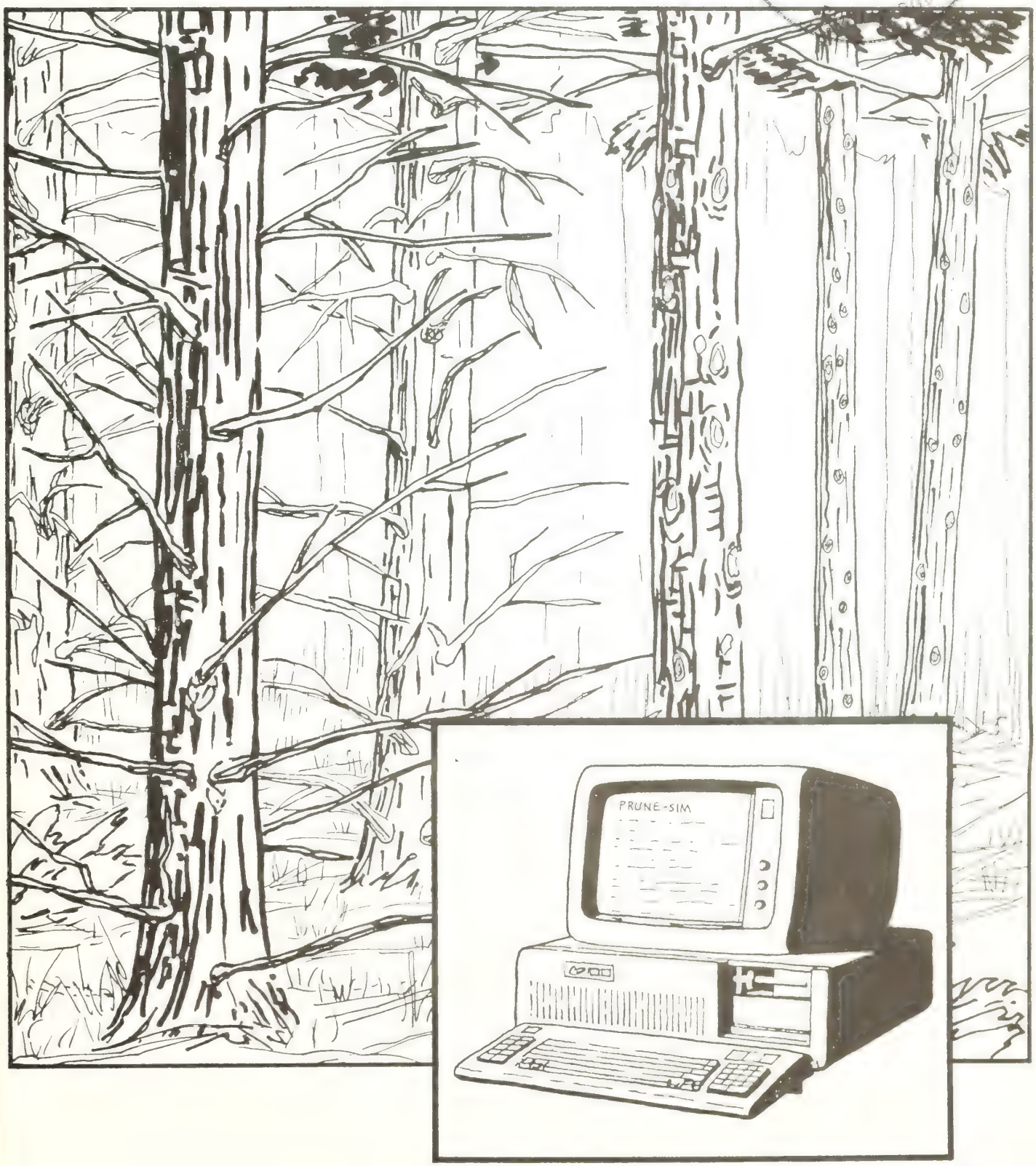
do NOT detach label

Agriculture
Forest Service
Pacific Northwest Research Station
Research Paper PNW-RP-390

Financial Analysis of Pruning Coast Douglas-Fir

Roger D. Fight, James M. Cahill, Thomas D. Fahey, and Thomas A. Snellgrove

OLYMPIA, WA
JAN 29 1988
DOCUMENTS



Authors

ROGER D. FIGHT is principal economist, JAMES M. CAHILL is research forester, THOMAS D. FAHEY is research forester, and THOMAS A. SNELLGROVE is principal research forest products technologist, Forestry Sciences Laboratory, P.O. Box 3890, Portland, Oregon 97208.

Abstract

Fight, Roger D.; Cahill, James M.; Fahey, Thomas D.; Snellgrove, Thomas A. 1987. Financial analysis of pruning coast Douglas-fir. Res. Pap. PNW-RP-390. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 17 p.

Pruning of coast Douglas-fir was evaluated; recent product recovery information for pruned and unpruned logs for both sawn and peeled products was used. Dimensions of pruned and unpruned trees were simulated with the Douglas-fir stand simulator (DFSIM). Results are presented for a range of sites, ages at time of pruning, ages at time of harvest, product prices, and interest rates, and for both fertilized and unfertilized regimes.

Summary

Unpruned stands of young-growth Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) yield little clear material with the kinds of regimes now being commonly implemented in western Oregon and western Washington. A recent recovery study provides the basis for comparing the grade recovery from the butt logs of pruned trees with that of unpruned trees (Cahill and others, in press). A spreadsheet program was developed and used to simulate the increase in grade recovery and financial return from pruning. The analysis of financial return was done with DFSIM growth and yield data reported by Curtis and others (1982). The analysis included a range of sites, ages at time of pruning, ages at time of harvest, prices, and interest rates, and both fertilized and unfertilized regimes.

Results showed that a 5-year difference in the time of pruning can make a substantial difference in the financial return. The earlier age at pruning always gave a higher return. The number of years between pruning and harvest that gives the highest return from pruning depends on the site, the interest rate, and whether or not the stand is fertilized. At a 4-percent interest rate, the return was generally highest when the harvest was 40 to 50 years after pruning. At an 8-percent interest rate, the return was generally highest when the harvest was 30 to 40 years after pruning.

The financial return from pruning stands on an unfertilized site 145 (50-year site index) was roughly twice that from an unfertilized site 85. Fertilization substantially increases the return from pruning, especially on low sites. The return from pruning stands on a fertilized site 85 is almost as high as that from an unfertilized site 125.

Keywords: Simulation, pruning, Douglas-fir (coast), product recovery, financial analysis, forest product value.

Contents

1 **Introduction**

1 **Assumptions**

1 Yield Data

2 Log and Tree Dimensions

2 Price Assumptions

3 Other Key Assumptions

3 **Results**

12 **Comparisons**

12 Age at Pruning

12 Interval Between Pruning and Harvest

13 Site

14 Fertilization

14 Wood Product Prices

16 **Conclusions**

16 **Metric Equivalents**

17 **Literature Cited**

Introduction

Although several evaluations have been made of pruning coast Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) over the years (Dimock and Haskell 1962, Dobie and Wright 1978, Fensom 1957, McBride 1961, Shaw and Staebler 1950), pruning has not been adopted as an operational practice on any significant area in the Pacific Northwest. The financial return from pruning comes from the increase in value of clear wood that will be produced from pruned trees. Given the short harvest cycles used in current management of Douglas-fir and its limb-retention characteristics, little clear wood will be produced in unpruned young-growth stands. The crucial question is whether the increase in value from additional clear wood will justify the investment in pruning. The purpose of this paper is to provide the results of financial evaluations of pruning managed stands of Douglas-fir across a range of sites, management regimes, prices, and interest rates. These evaluations are based on a new study of product grade recovery from pruned Douglas-fir (Cahill and others, in press). A spreadsheet template, PRUNE-SIM (Fight and others 1987), which works on a personal computer with Lotus 1-2-3 spreadsheet software, was used in the analysis.[1] This template can be used to do further sensitivity analysis, to look at other regimes, or to otherwise customize the results to a particular owner, agency, or geographic area.

Specific questions about financial return from pruning are addressed:

1. What is the best age for pruning coast Douglas-fir?
2. What is the best interval between pruning and harvest?
3. How does site productivity affect financial return?
4. How does fertilization affect financial return?
5. How do wood product prices affect financial return?

The financial returns reported in this paper are the present values of the increases in product value resulting from pruning. This financial return is the maximum amount that can be spent for pruning without reducing the rate of return on investment below the specified rate. No pruning costs are reported. The user must provide information on the cost of pruning to determine the present net value of pruning (present value net of pruning cost).

First, we discuss the assumptions and limitations of the analysis that are needed to evaluate the results and conclusions. We then present a series of graphs that result from many simulations. Lastly, we show graphs that address the five questions above.

Assumptions

Yield Data

All the evaluations in this report are based on regimes reported in the published Douglas-fir simulator (DFSIM) yield tables (Curtis and others 1982). These regimes use the DFSIM default thinnings. Some regimes include fertilization. We use these regimes to obtain simulated tree descriptions needed for estimating log volumes. This analysis is based on pruning a 17-foot butt log above a 1-foot stump. This assumption is imposed by the recovery study, in which all the pruned trees had been pruned to yield a 17-foot clear log. Pruning is assumed to have no impact on tree growth, so the volume with and without pruning is the same. According to the literature (Staebler

[1] The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture of any product or service to the exclusion of others that may be suitable.

1963, Stein 1955), pruning has little effect on tree growth if less than one-third of the live crown is removed. Another assumption is that 5 percent of the pruned trees are lost before final harvest; this assumption is a guess. Poor selection of trees for pruning, careless selection of trees for logging, and careless logging could result in much higher losses of pruned trees. The mortality in stands included in the regimes used here ranges from about 6 to 10 percent.

Log and Tree Dimensions

Log diameters are determined from a tree profile equation described in the PRUNE-SIM users guide (Fight and others 1987). For this analysis, we assumed that the number of pruned trees would not exceed the number of trees that could be carried to harvest age so that all the pruned trees were harvested at the final harvest. We also assumed that the largest trees in the stand would be selected for pruning. All regimes began with 300 trees per acre, but the number of pruned trees was 60, 80, or 100, depending on how many could be carried to final harvest. Because the pruned trees are one-fifth to one-third of the stand, we used the DFSIM reported height of the 40 tallest trees (HT40) rather than the height of the tree of average volume (Lorey height) to represent the height of the pruned trees at time of pruning. At time of harvest, almost all the trees are pruned trees, so we used Lorey height rather than HT40. The diameter of the pruned trees at time of pruning was estimated by determining the median diameter of the pruned trees; a normal distribution of tree diameters was assumed. The procedure is described in the PRUNE-SIM users guide (Fight and others 1987). At time of harvest, the stand diameter reported in DFSIM is used without modification (Curtis and others 1982).

Price Assumptions

The analysis included two sets of price assumptions. The "low" assumption is based on 1986 prices (Random Lengths 1987, Warren 1987). We regard this as a very conservative assumption for this analysis; prices in 1986 were substantially below the long-term trend in product prices, and preliminary projections from the southern timber supply study[2] indicate that prices should increase substantially above the 1986 level over the next several decades. Our "high" price assumption is based on those projections for the year 2030. The following tabulation shows the prices:

	Low price	High price
	(Dollars per thousand board feet)	
Lumber:		
Select	566	820
Select Structural	240	447
Standard and Better	191	338
Utility and Economy	111	198
	(Dollars per thousand square feet, 3/8-inch basis)	
Veneer:		
A and B	180	324
C and D	90	162

Veneer prices are for green veneer and are quoted per thousand square feet on a finished panel size.

[2] Preliminary data from the southern timber supply study on file with Richard Haynes, Economist, USDA Forest Service, Forestry Sciences Laboratory, P.O. Box 3890, Portland, OR 97208.

Other Key Assumptions

In our analysis, we assumed no differences in costs in stand management, logging, or manufacturing after pruning, except in veneer manufacturing, for which we assumed that the AB veneer from pruned logs would be produced at a cost saving of $88 per thousand square feet (3/8-inch basis) of 1/10-inch veneer. This saving results from a dramatic reduction in the number of patches required.

Another key assumption of this analysis is that the future unpruned trees will be like the unpruned (control) trees in the recovery study (Cahill and others, in press). The control stands were more heavily stocked and had more thinnings than is likely in the future. This resulted in a bias against pruning because these control trees probably had smaller limbs than if they had been grown under lighter stocking and with fewer entries. Another bias in our results against pruning for lumber resulted from the recovery's being based on a production-oriented sawmill. A greater difference in value between the pruned and unpruned logs would be achieved in a mill oriented to sawing for grade, although this would be partially offset by higher manufacturing costs.

Results

Figures 1 to 11 show the maximum amount per tree that could be spent to prune the butt logs without reducing the rate of return below the specified rate. The difference between this value and the estimated cost of pruning (supplied by the user) is net present value from pruning. Each graph shows the results for three interest rates: 4, 6, and 8 percent. Each graph shows the present value for one product (lumber or veneer), one price assumption (high or low), one King's (1966) 50-year site index class (85, 105, 125, or 145), one age at time of pruning, and a series of ages at harvest. Each figure has a series of graphs that show the results for various regimes for one product and one price assumption. Figure 1 shows the present value from pruning for lumber under the high price assumption; figure 2, under the low price assumption. Figures 3 and 4 give the same information for veneer. Figures 5-8 show a series of regimes that include two or three fertilizations with 200 pounds of nitrogen, depending on whether the age at harvest permits the third application of fertilizer. Figure 5 is for lumber under the high price assumption and figure 6 under the low. Figures 7 and 8 give the same information for veneer.

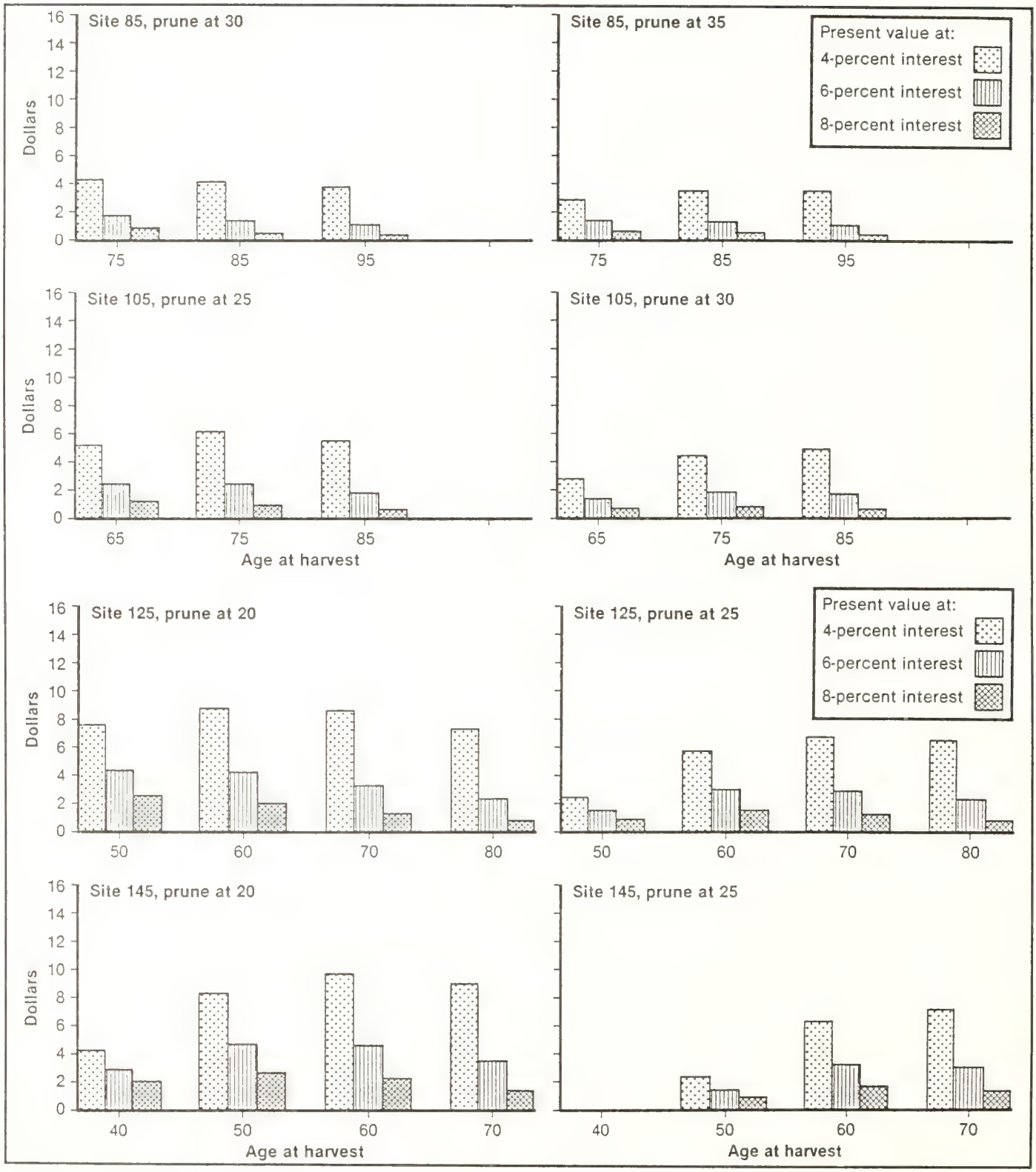


Figure 1—Increase in present value per tree from pruning unfertilized stands for lumber with the high price assumption.

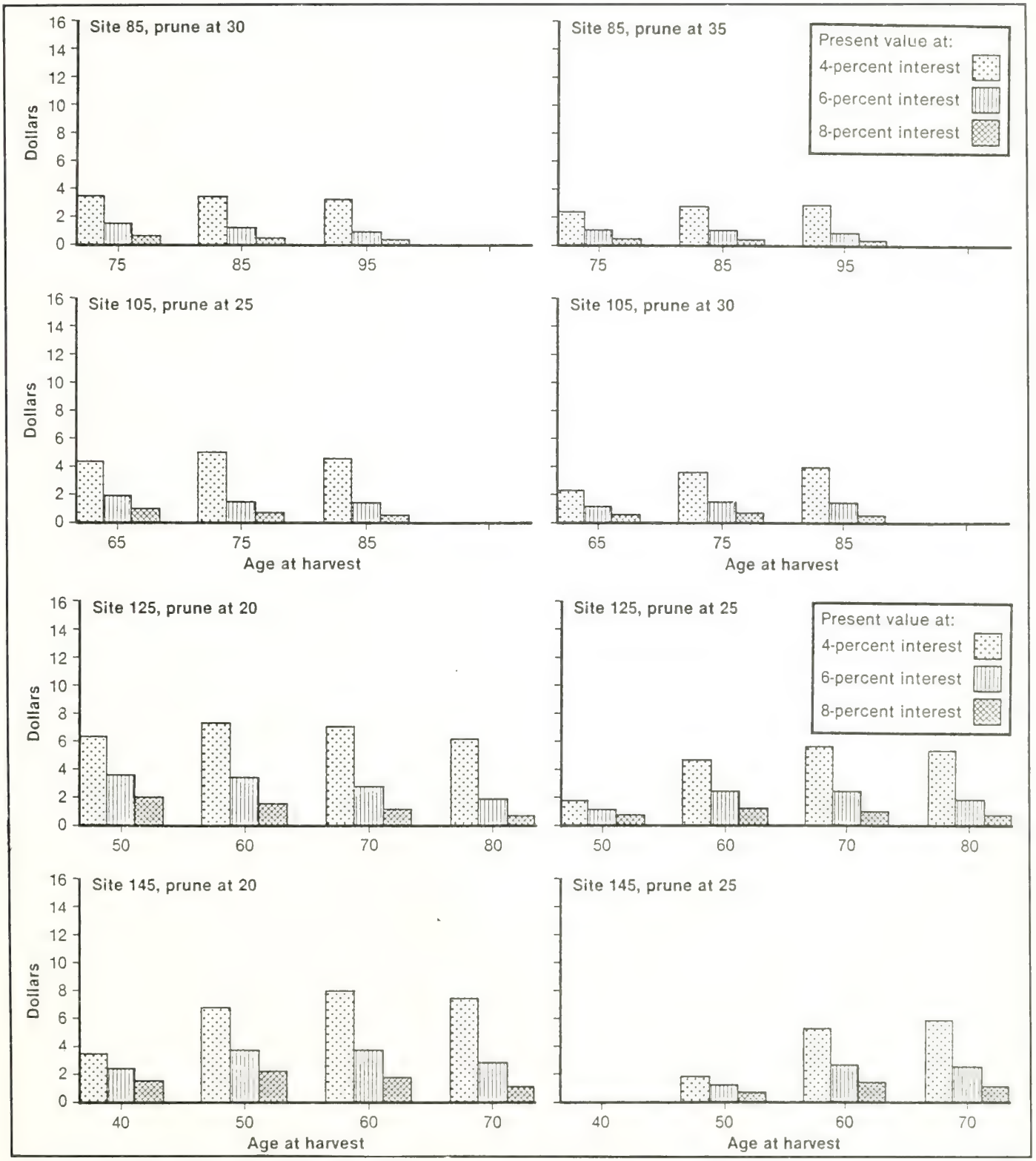


Figure 2—Increase in present value per tree from pruning unfertilized stands for lumber with the low price assumption.

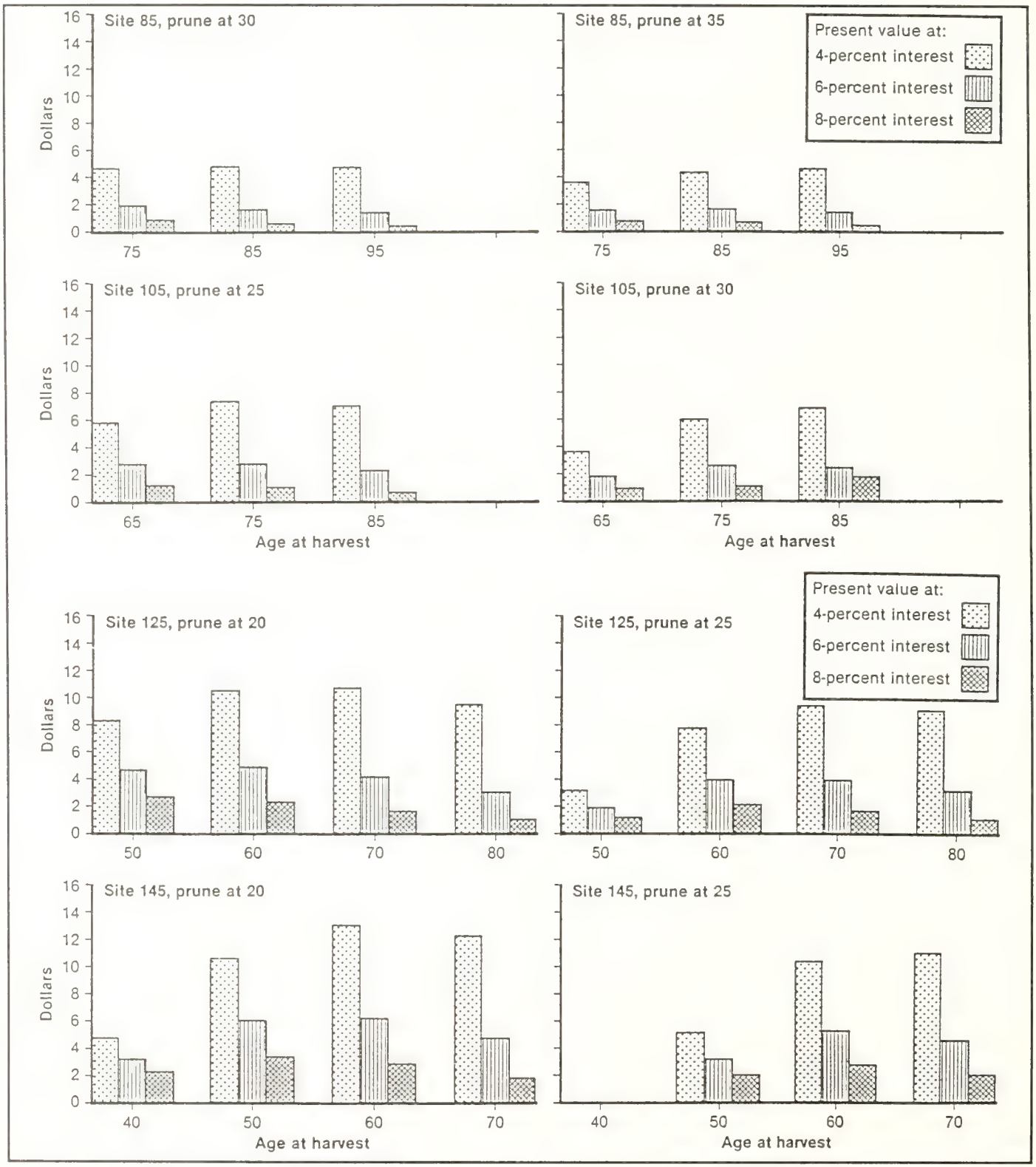


Figure 3—Increase in present value per tree from pruning unfertilized stands for veneer with the high price assumption.

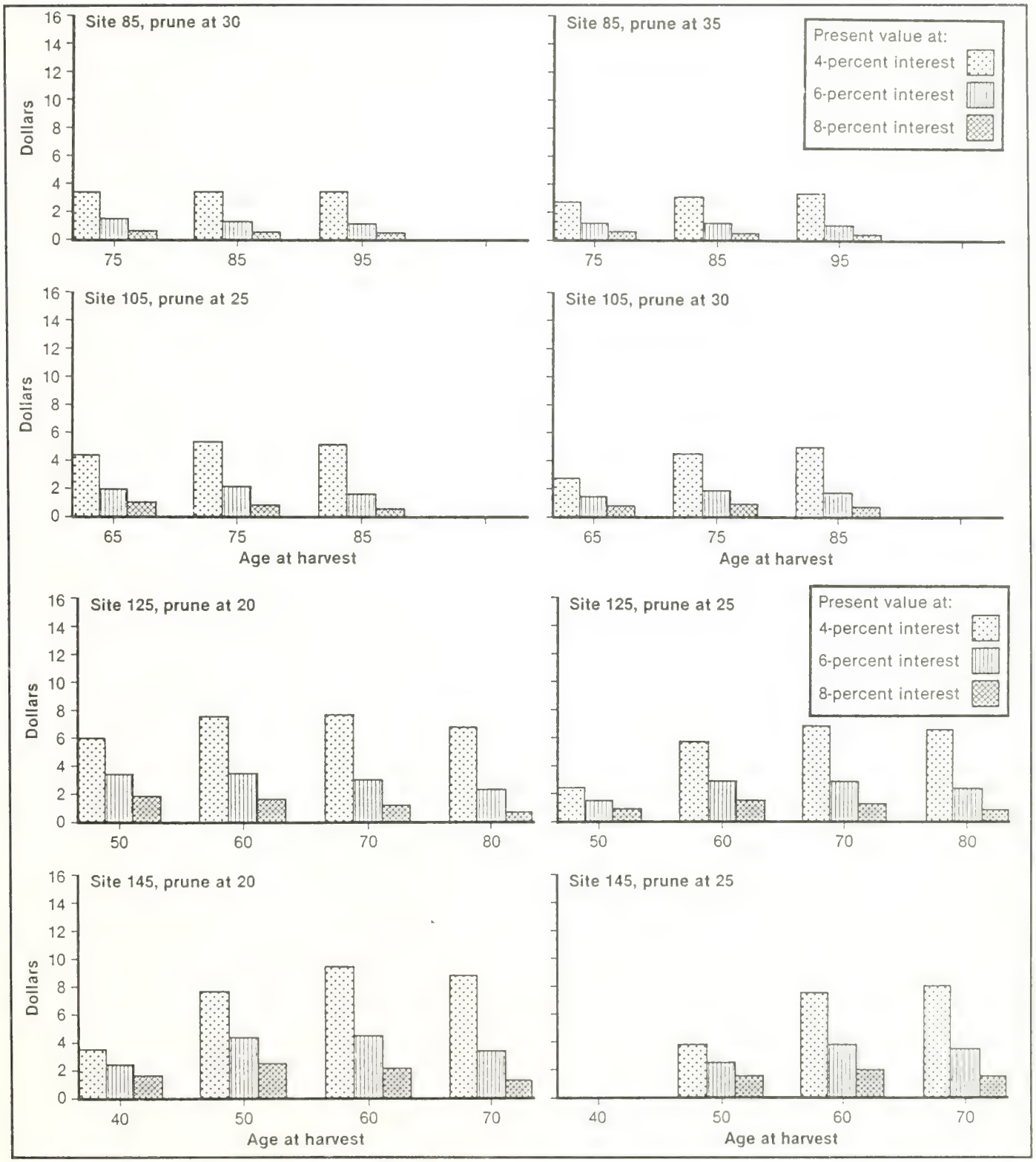


Figure 4—Increase in present value per tree from pruning unfertilized stands for veneer with the low price assumption.

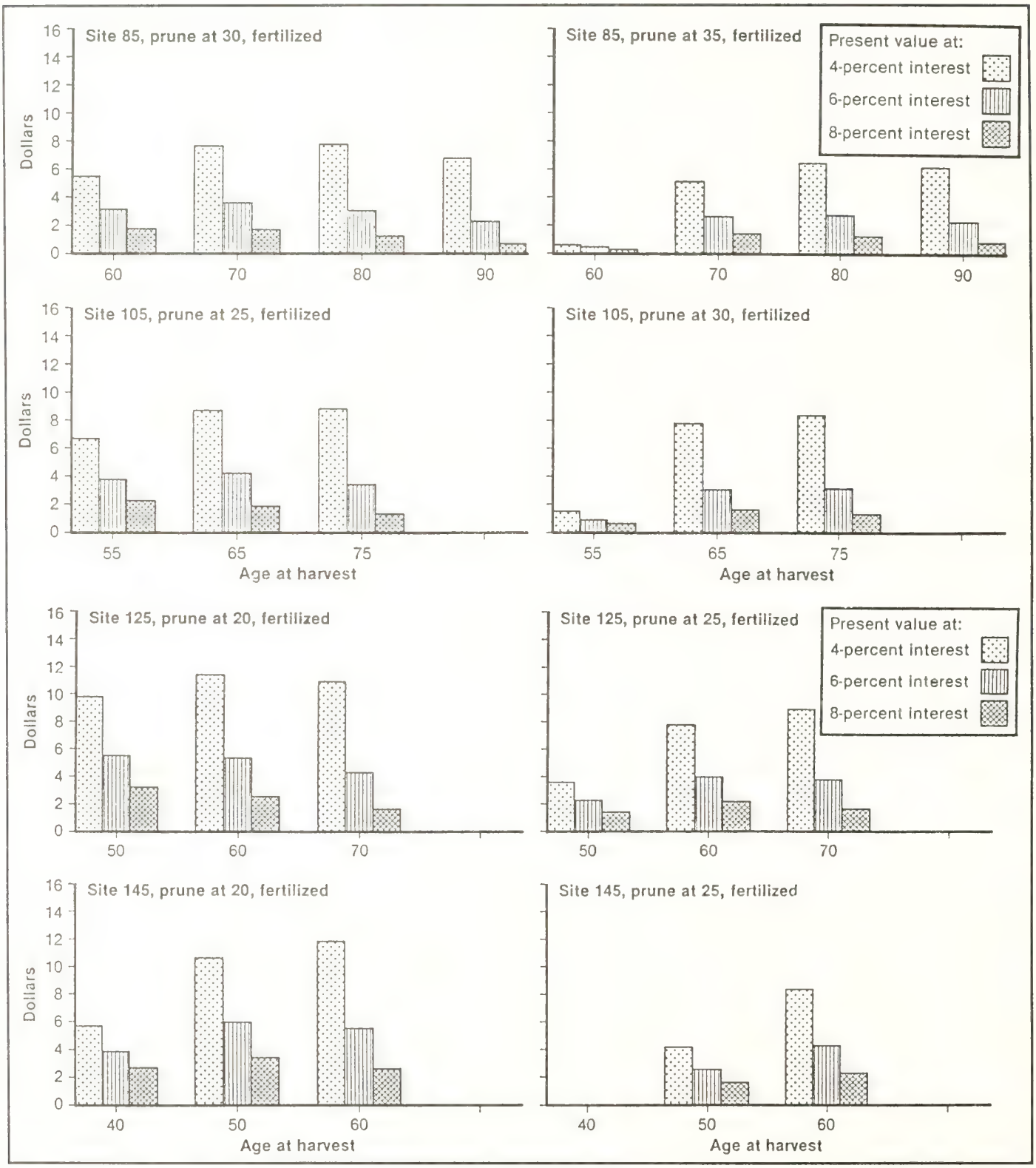

Site 85, prune at 30, fertilized
Site 85, prune at 35, fertilized
Present value at:
4-percent interest
6-percent interest
8-percent interest
Site 105, prune at 25, fertilized
Site 105, prune at 30, fertilized
Site 125, prune at 20, fertilized
Site 125, prune at 25, fertilized
Site 145, prune at 20, fertilized
Site 145, prune at 25, fertilized
Dollars
Age at harvest

Figure 5—Increase in present value per tree from pruning fertilized stands for lumber with the high price assumption.

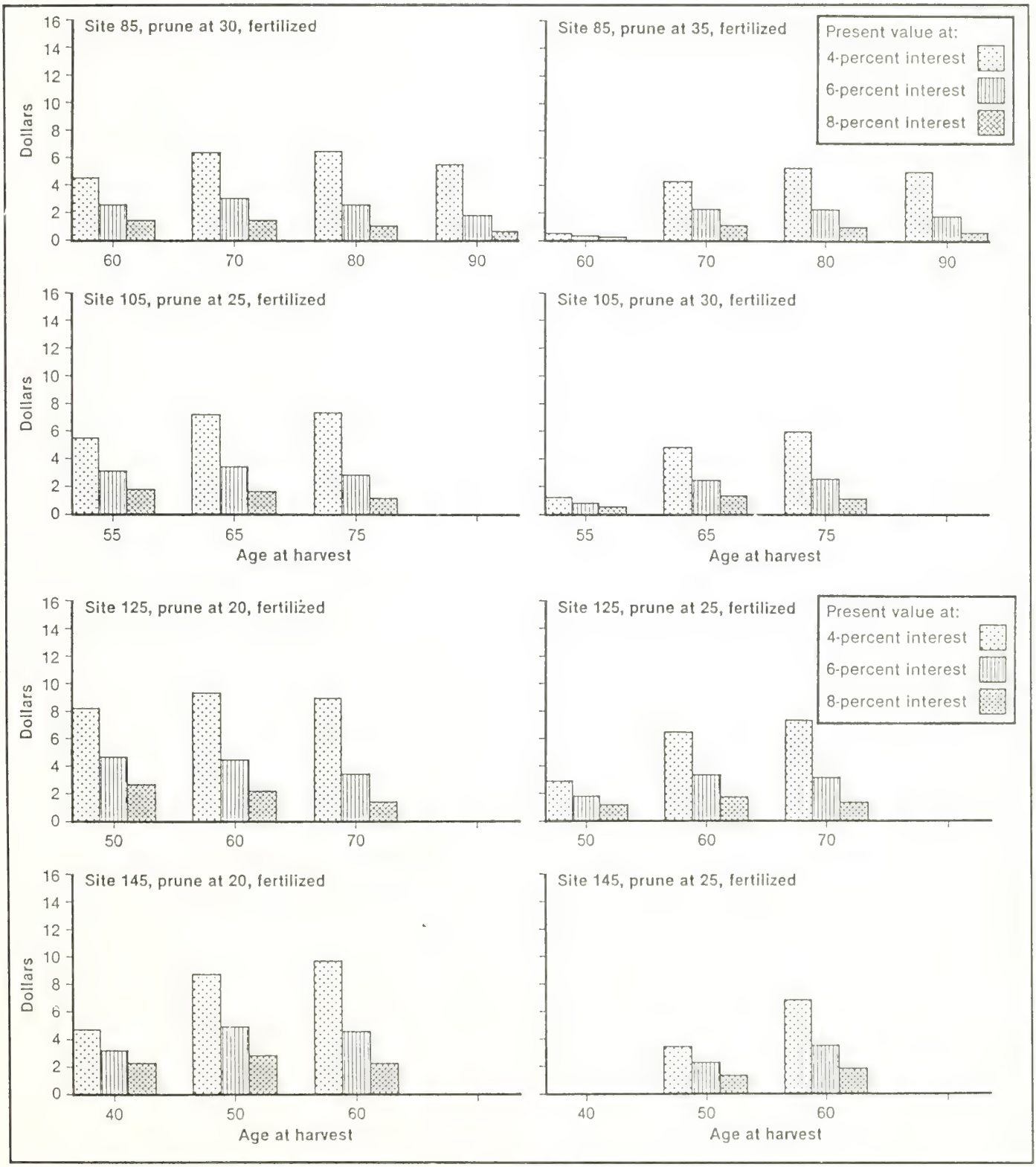

Site 85, prune at 30, fertilized
Site 85, prune at 35, fertilized
Present value at:
4-percent interest
6-percent interest
8-percent interest
Site 105, prune at 25, fertilized
Site 105, prune at 30, fertilized
Site 125, prune at 20, fertilized
Site 125, prune at 25, fertilized
Site 145, prune at 20, fertilized
Site 145, prune at 25, fertilized
Dollars
Age at harvest

Figure 6—Increase in present value per tree from pruning fertilized stands for lumber with the low price assumption.

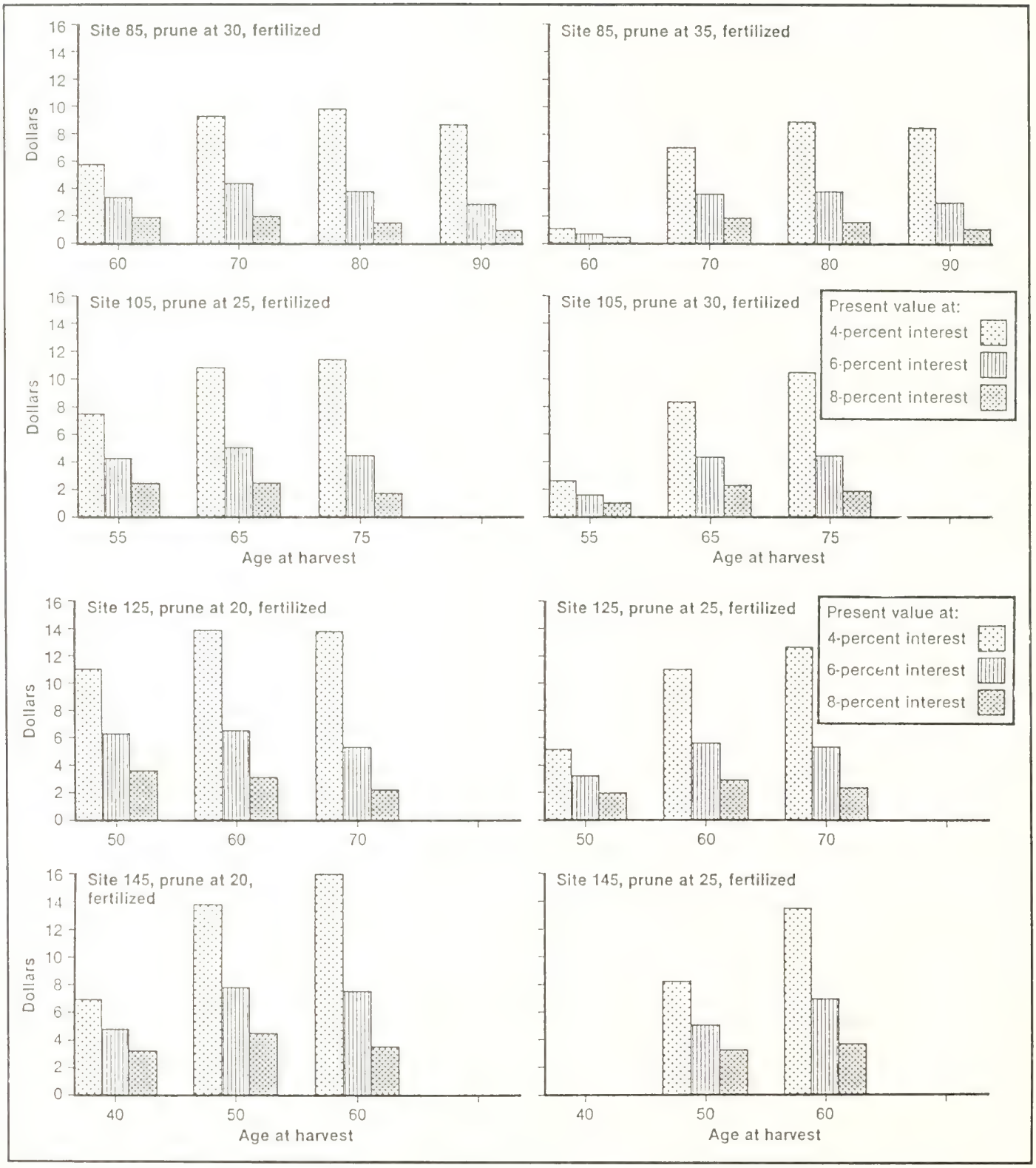

Site 85, prune at 30, fertilized
Site 85, prune at 35, fertilized
Site 105, prune at 25, fertilized
Site 105, prune at 30, fertilized
Site 125, prune at 20, fertilized
Site 125, prune at 25, fertilized
Site 145, prune at 20, fertilized
Site 145, prune at 25, fertilized
Dollars
Age at harvest
Present value at:
4-percent interest
6-percent interest
8-percent interest

Figure 7—Increase in present value per tree from pruning fertilized stands for veneer with the high price assumption.

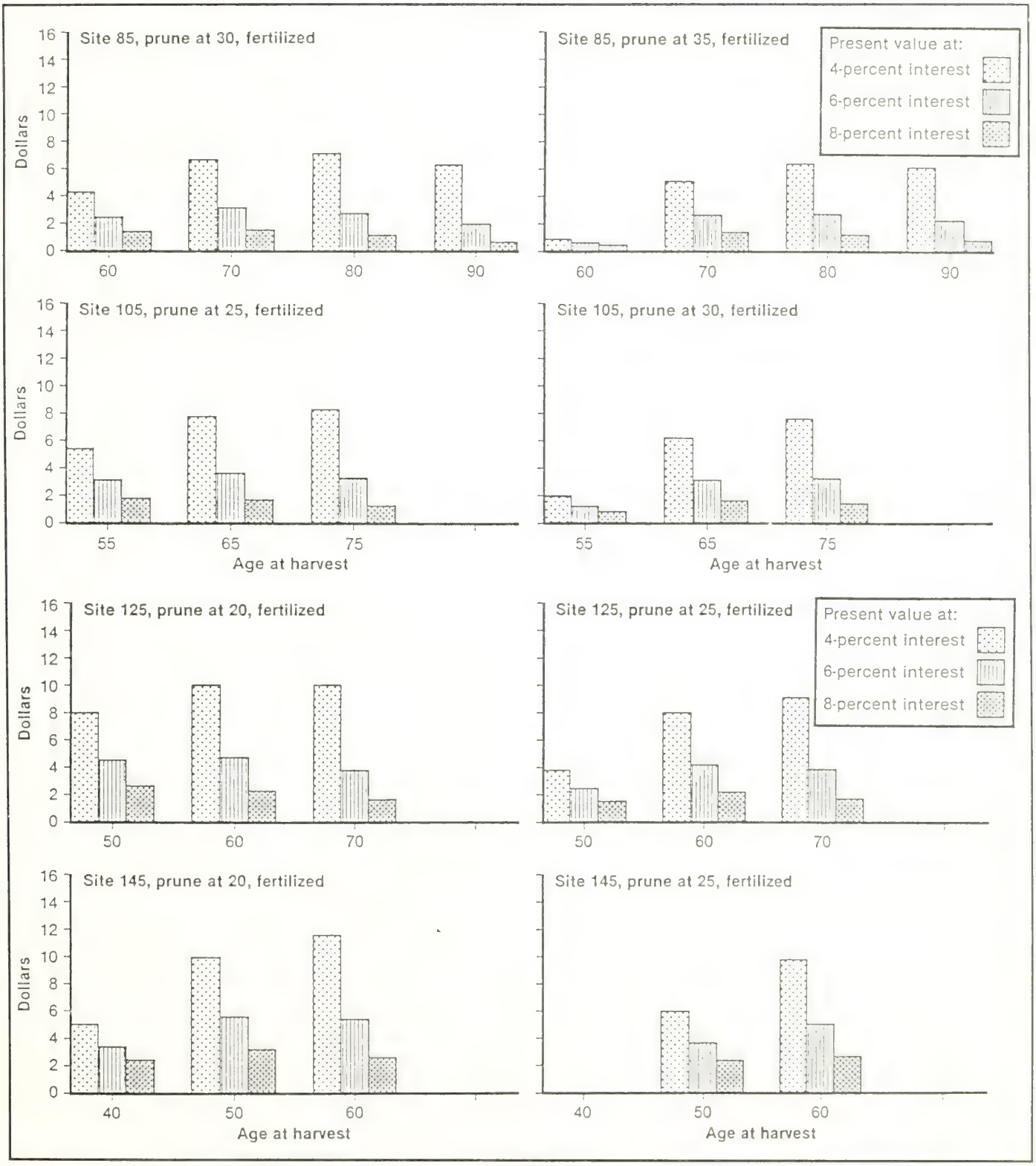

Site 85, prune at 30, fertilized
Site 85, prune at 35, fertilized
Present value at:
4-percent interest
6-percent interest
8-percent interest
Site 105, prune at 25, fertilized
Site 105, prune at 30, fertilized
Site 125, prune at 20, fertilized
Site 125, prune at 25, fertilized
Site 145, prune at 20, fertilized
Site 145, prune at 25, fertilized
Dollars
Age at harvest

Figure 8—Increase in present value per tree from pruning fertilized stands for veneer with the low price assumption.

Comparisons

Age at Pruning

Figure 9 shows how the present value of pruning for the unfertilized regimes is affected by the age at pruning. The present value for later pruning is compared with the present value for the earlier pruning. The earlier age at pruning was selected as the first age (of ages ending in zero or five) when trees could be pruned to 18 feet without removing more than one-third of the live crown. Using data supplied from Reukema and Smith (1987), we estimated that the trees to be pruned must be a minimum of 43 feet tall to meet this criterion. The later age at pruning was 5 years later than the earlier age at pruning. These comparisons are between the regimes with the harvest age that gives the highest present value from pruning for each age at pruning. The results show that, in every case analyzed, the present value from pruning is higher for pruning at the earliest possible time. Although a comparable set of graphs for fertilized stands is not shown, the same conclusion applies to those regimes as well. For a specified harvest age, however, it will sometimes be better to delay pruning. For example, with a harvest age that is older than the one that gives the highest return from pruning, it may be better to delay pruning to reduce the number of years that the returns from pruning are delayed. The conclusion about pruning at the earliest possible time could be altered by the costs of pruning only if it cost more to prune at the earlier time. A practical consideration that is not accounted for in this analysis is whether or not the ability of the forester to select crop trees for pruning is significantly affected by the 5-year difference in the age at time of pruning.

Interval Between Pruning And Harvest

The effect of the interval between pruning and harvest on the return from pruning can be seen in figures 1-8. For a particular situation and age at time of pruning, each graph shows the present value from pruning for a range of harvest ages. These comparisons typically show a reduced number of pruned trees for the longer rotations because the number of trees that can be carried to rotation diminishes with increasing age at harvest. This means that, although longer rotations may have a higher return from pruning per tree, they may also have a lower return from pruning per acre. We suggest, however, that the per-tree figure is the more relevant comparison for two reasons. First, the cost of pruning is more closely related to the number of trees pruned than to the number of acres pruned. If costs are directly related to the number of trees pruned, then the present value per tree minus the cost of pruning per tree is a valid comparison. Second, a shortage of acres to prune in the future is unlikely, and the landowner can prune as many acres as needed to get the volume of pruned trees desired.

What conclusions can be drawn from these comparisons of age at harvest? Many of these comparisons show that there is a point beyond which return from pruning declines as the age at harvest is increased because the discounting of returns overtakes the rate of increase in value and causes the present value to decrease. This point occurs at an earlier age for higher interest rates. For example, the "Site 145, prune at 20" regime in figure 1 shows that at 4-percent interest this decrease occurs between harvest ages 60 and 70; at 6- or 8-percent interest, this decrease occurs between harvest ages 50 and 60.

An analysis of the results for each situation and age at pruning showed the following: At 4-percent interest, the interval after pruning that gave the highest present value from pruning was usually 40, 45, or 50 years; at 8-percent, the interval was usually 30, 35, or 40 years. The shorter intervals are associated with higher sites and fertilized stands where the rate of growth of clear wood is more rapid. At 6- and 8-percent interest rates for regimes with delayed pruning, the interval between pruning and

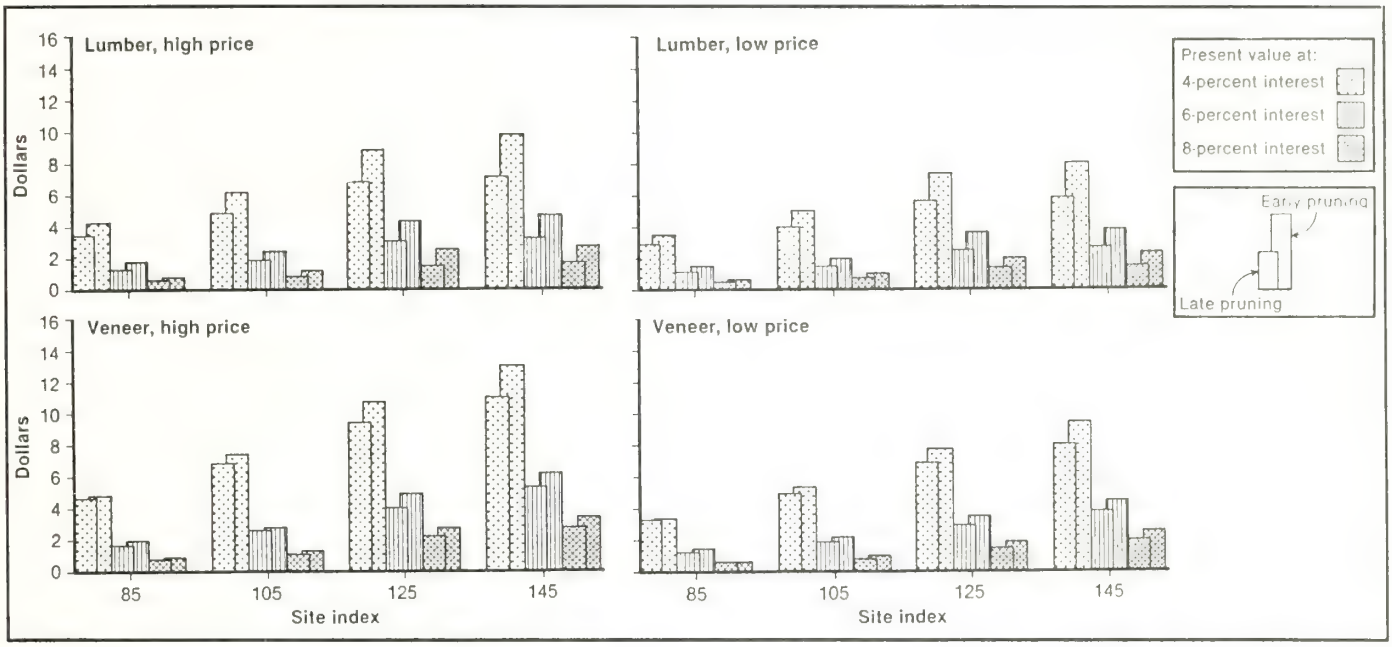


Figure 9—Comparison of increase in present value per tree from early and late pruning of unfertilized stands for lumber and veneer.

harvest that has highest present value increased by 5 years in most cases. The results with the 4-percent interest rate are mixed for regimes where pruning is delayed; about half show a higher value for a longer interval between pruning and harvest, and half show a lower value for a longer interval. This results from rounding and indicates that with a 4-percent interest rate, no significant effect on optimal time after pruning results from delaying the pruning.

The time after pruning that gives the highest return from pruning cannot be interpreted as the optimal age to harvest the stand. The optimal harvest age with pruning must be determined by a more complicated analysis because the harvest age affects the return from the whole management regime.

Site

The effect of site on the return from pruning can be seen in figure 9. Each graph in figure 9 shows the return from pruning for a range of sites. The effect of site index can be seen in a particular product-price-interest rate combination across sites. The general result is that the return from pruning is about twice as much on site index 145 as on site 85. The returns on sites 105 and 125 fall between. It should be obvious that investments in pruning will be most favorable on sites where the rate of growth of clear wood is highest as long as the rate of growth is not so rapid that it causes a decrease in quality. This relative difference will increase when the user subtracts the pruning cost from the present value of pruning to get the present net value of pruning.

Fertilization

Like the effect of site, the effect of fertilization should be obvious. Figure 10 shows the effect of fertilization on the present value of pruning. The regimes with fertilization are based on the regimes with repeated fertilizations in the DFSIM yield tables (Curtis and others 1982). The number of fertilizations for each site in the yield tables is three, but because they start at different ages on different sites, the number of fertilizations in the pruning evaluations varies by site and the harvest age. In some cases the harvest is taken at a time that would have made the preceding fertilization infeasible because of the short time between the fertilization and harvest. In those cases, however, the effect of the fertilization is minimal so the result is not much different than if that fertilization had been omitted. Figure 10 clearly demonstrates the interaction effect of fertilization and pruning; pruning a stand that will be fertilized yields a significantly higher return from pruning than if the stand is not fertilized. This relative difference will increase when the cost of pruning is subtracted from the present value of pruning to get the present net value of pruning.

Wood Product Prices

Figure 11 shows the present value from pruning with the low price assumption compared with the present value from pruning with the high price assumption. Under both price assumptions, the return from pruning is somewhat higher for veneer. Concluding, however, that whether the pruned logs are used for lumber or veneer makes little difference is not necessarily correct. The gross product value of both pruned and unpruned logs happens to be lower for veneer than for lumber for all regimes under both price assumptions. Manufacturing costs must be considered before the net value of pruned and unpruned logs in both lumber and veneer can be determined. This analysis allows us to conclude only that if the butt logs will be made into a particular product, the increase in present value will be as shown for the specified conditions.

The difference in return from pruning between the low and high price assumptions results solely from the difference in price between the highest grades and the lower grades of products. If prices were increased by increasing the price for all grades by a constant amount, the return from pruning would not be affected. Projections of wood product prices must be regarded as uncertain guides to future prices. Projections of the differences in prices between grades must be regarded as even more uncertain. Because of the uncertainty, we used both current and "best guess" future prices in the analysis. Because of this uncertainty and the fact that the return from pruning is quite sensitive to the difference in prices between grades, many users of PRUNE-SIM will want to do additional sensitivity analyses with prices.

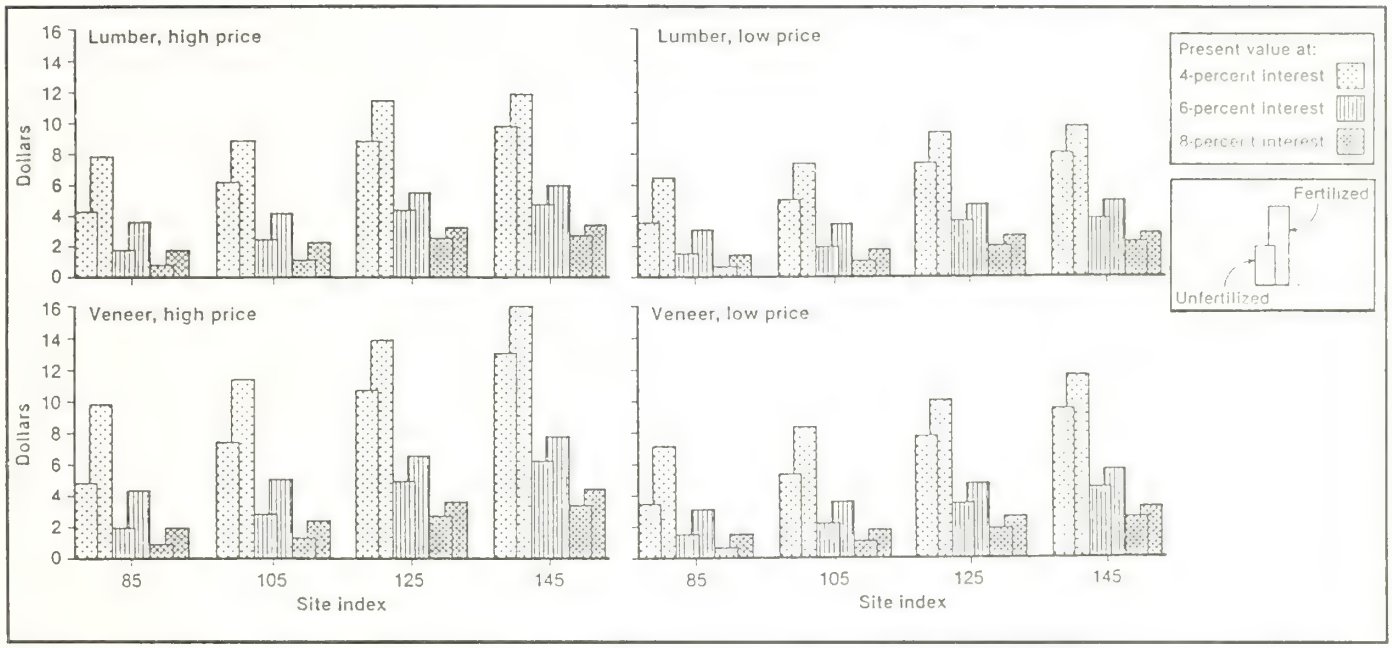


Figure 10—Comparison of increase in present value from pruning of unfertilized and fertilized stands for lumber and veneer.

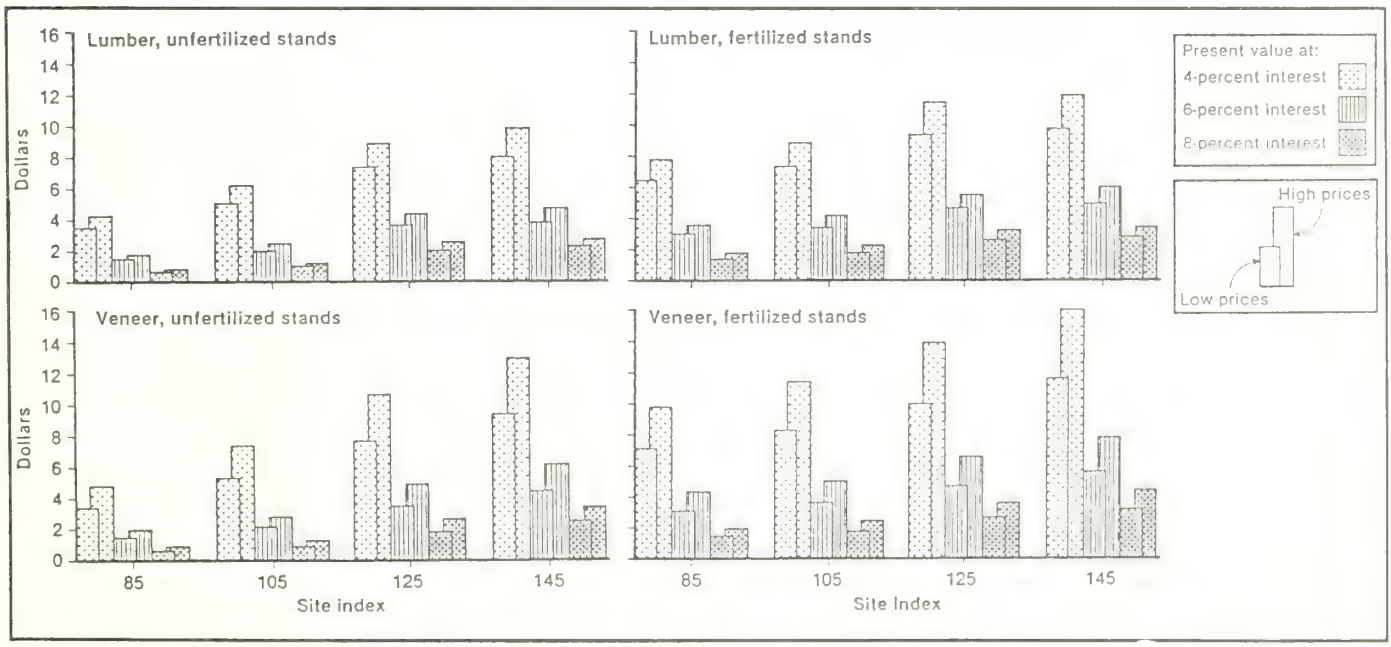


Figure 11—Comparison of increase in present value from pruning of unfertilized and fertilized stands for lumber and veneer with low and high prices.

Conclusions

What can we say about the question, "Will the increase in value justify the investment in pruning?" The results clearly show that the expected increase in present value from pruning is often more than $3 per tree. At a 4-percent interest rate, almost all regimes in figures 9-11 exceed $3 per tree. At a 6-percent interest rate, some of the regimes exceed $3 per tree; at an 8-percent interest rate, only one regime exceeds $3 per tree. Apparently, even with 1986 prices, sometimes pruning will return more than $3 per tree with an interest rate of 4 or 6 percent. With an increase in price premium for high grade products, the number of situations that will return $3 per tree increases rapidly. With wages, benefits, and equipment costs of $15 per hour, the cost of pruning will be $3 per tree at a rate of five trees per hour. Our limited information indicates that in many situations a rate of five trees per hour could easily be achieved.

What about the other costs of pruning not considered in this analysis? One is the cost of keeping records on the location of pruned stands and perhaps pruned trees in those stands. Such records are essential to ensure that the pruned trees are not inadvertently harvested prematurely. Also, the seller of stumpage must be able to convince potential buyers that the clear wood will translate into increased product value in the mill. Where competition for stumpage between mills that have the capability to effectively use this clear material exists, proper appraisal and documentation should ensure that the stumpage seller gets a large part of the increase in value. In areas with limited competition or no mills that can effectively use this clear material, the seller may not be able to get the increased value.

One potential benefit from pruning was not considered in this analysis. Where higher planting densities are predicated on the need for reducing the size of limbs on the lower portion of the bole, that need is eliminated with pruning. This may result in a lower planting cost that can be attributed to the decision to prune.

In spite of the uncertainties about the assumptions and relations used in this analysis, we believe that the analysis represents the best available information and provides a reasonable basis for forest managers to draw some conclusions about the financial feasibility of pruning coast Douglas-fir.

Metric Equivalents

1 inch = 2.54 centimeters

1 foot = 0.305 meter

1 cubic foot = 0.028 cubic meter

1 acre = 0.4047 hectare

1 pound = 0.45 kilogram

Literature Cited

Cahill, James M.; Snellgrove, Thomas A.; Fahey, Thomas D. [In press]. Lumber and veneer recovery from pruned Douglas-fir. Forest Products Journal.

Curtis, Robert O.; Clendenen, Gary W.; Reukema, Donald L.; DeMars, Donald J. 1982. Yield tables for managed stands of coast Douglas-fir. Gen. Tech. Rep. PNW-135. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 182 p.

Dimock, Edward J.; Haskell, Henry H. 1962. Veneer grade yield from pruned Douglas-fir. Res. Pap. 48. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 15 p.

Dobie, J.; Wright, D.M. 1978. Economics of thinning and pruning—a case study. Forestry Chronicle. 54(1): 34-38.

Fensom, K.G. 1957. Veneer recovery from pruned and unpruned Douglas-fir logs. Natl. Res. Rep. V-1022. Vancouver, BC: Canadian Department of Northern Affairs, Forest Products Laboratory. 14 p.

Fight, Roger D.; Cahill, James M.; Snellgrove, Thomas A.; Fahey, Thomas D. 1987. PRUNE-SIM users guide. Gen. Tech. Rep. PNW-GTR-209. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 22 p.

King, James E. 1966. Site index curves for Douglas-fir in the Pacific Northwest. Weyerhaeuser For. Pap. 8. Centralia, WA: Weyerhaeuser Forest Resource Center. 49 p.

McBride, C.F. 1961. Lumber grades recovered from pruned Douglas-fir. Forestry Chronicle. 37(4): 390-393.

Random Lengths Publications, Inc. c1987. 1986 Random Lengths yearbook. Eugene, OR: Random Lengths Publications, Inc. 202 p.

Reukema, Donald L.; Smith, J. Harry G. 1987. Development over 25 years of Douglas-fir, western hemlock, and western redcedar planted at various spacings on a very good site in British Columbia. Res. Pap. PNW-RP-381. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 46 p.

Shaw, Elmer W.; Staebler, George R. 1950. Financial aspects of pruning. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 45 p.

Staebler, George R. 1963. Growth along the stems of full crowned Douglas-fir trees after pruning to specified heights. Journal of Forestry. 61(2): 124-127.

Stein, William I. 1955. Pruning to different heights in young Douglas-fir. Journal of Forestry. 53(5): 352-355.

Warren, Debra D. 1987. Production, prices, employment, and trade in Northwest forest industries, fourth quarter 1986. Resour. Bull. PNW-144. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 55 p.

Flght, Roger D.; Cahlll, James M.; Fahey, Thomas D.; Snellgrove, Thomas A. 1987. Financial analysis of pruning coast Douglas-fir. Res. Pap. PNW-RP-390. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 17 p.

Pruning of coast Douglas-fir was evaluated; recent product recovery information for pruned and unpruned logs for both sawn and peeled products was used. Dimensions of pruned and unpruned trees were simulated with the Douglas-fir stand simulator (DFSIM). Results are presented for a range of sites, ages at time of pruning, ages at time of harvest, product prices, and interest rates, and for both fertilized and unfertilized regimes.

The **Forest Service** of the U. S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives—as directed by Congress—to provide increasingly greater service to a growing nation.

The U.S. Department of Agriculture is an Equal Opportunity Employer. Applicants for all Department programs will be given equal consideration without regard to race, color, sex, religion, or national origin.

Pacific Northwest Research Station
319 S.W. Pine St.
P. O. Box 3890
Portland, Oregon 97208

December 1987

U.S. Department of Agriculture
Pacific Northwest Research Station
319 S.W. Pine Street
P.O. Box 3890
Portland, Oregon 97208

BULK RATE
POSTAGE +
FEES PAID
USDA-FS
PERMIT No. G-40

Official Business
Penalty for Private Use, $300

do NOT detach label

United States
Department of
Agriculture

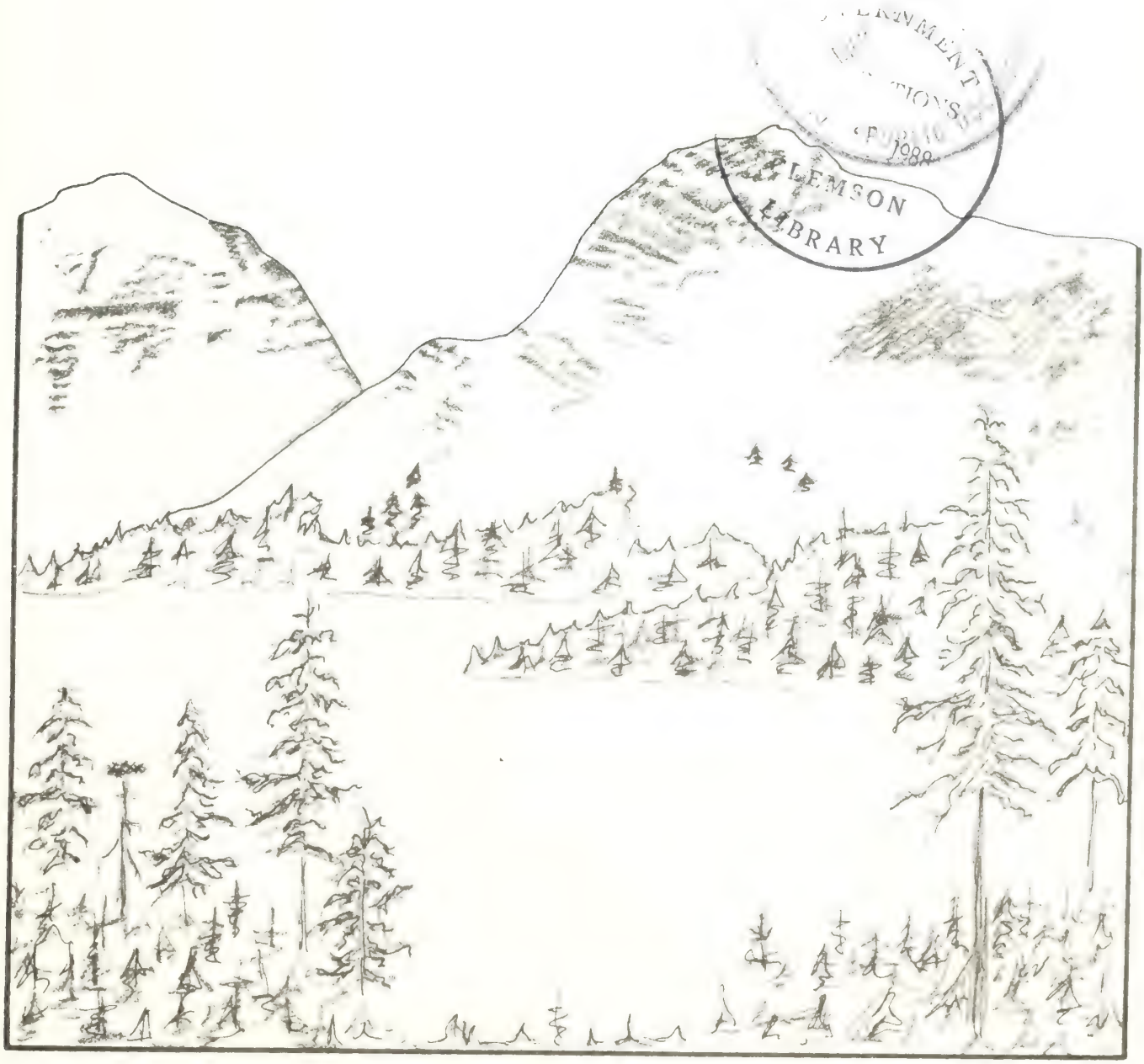
Forest Service

Pacific Northwest
Research Station

Research Paper
PNW-RP-391

Timber Productivity of Seven Forest Ecosystems in Southeastern Alaska

Willem W.S. van Hees



CLEMSON
LIBRARY

Author

WILLEM W.S. VAN HEES is a research forester, Forestry Sciences Laboratory, 201 East Ninth Avenue, Suite 303, Anchorage, Alaska 99501.

Abstract

van Hees, Willem W.S. 1988. Timber productivity of seven forest ecosystems in southeastern Alaska. Res. Pap. PNW-RP-391. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 10 p.

Observations of growth on Alaska-cedar (*Chamaecyparis nootkatensis*), mountain hemlock (*Tsuga mertensiana*), Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), and western redcedar (*Thuja plicata*) on seven forest ecosystems in southeastern Alaska were used to develop equations relating periodic annual cubic-foot volume growth percent (Pv) to tree diameter at breast height and percentage of live-tree stocking. Results showed differences in productivity between and within forest ecosystem soil groups.

Keywords: Soil productivity, growth rate, growth (plant) -)soil, Alaska (southeast).

Summary

Differences in timber productivity of seven forest ecosystem soils in southeastern Alaska were examined through regression analysis. The analysis attempted to relate tree volume growth percent to aspect, percentage of live-tree stocking, and tree diameter for five tree species growing on the seven ecosystem soils. The tree species were Alaska-cedar, mountain hemlock, western hemlock, Sitka spruce, and western redcedar. Necessary data were extracted from forest resource inventory data bases developed for southeastern Alaska. The regression analysis produced equations for 22 combinations of species and ecosystem soil. Aspect was the only proposed independent variable not statistically significant in any of the equations. Analysis of covariance showed most equations to be unique. The results of this study were consistent with estimates of Sitka spruce site index for each ecosystem made by Stephens and others (1968).

Contents

1 **Introduction**

1 **Study Area**

2 **Objectives**

2 **Methods**

2 Data

2 Forest Ecosystems

2 Dependent Variable

3 Independent Variables

4 Equation Form

4 **Results and Discussion**

4 Equations and Tests of Significance

6 Responses of Variables

7 Limitations

8 **Glossary**

10 **Literature Cited**

Introduction

An understanding of the relative differences in productivity among soils is important to forest managers for long-range planning. The most common measure of site productivity is site index: the height of dominant or codominant trees at some chosen age. This measure is commonly used in young, even-aged stands. It generally is not appropriate for estimating site productivity for stands of old-growth timber. Growth percent might be used instead for old-growth stands to rank their potential productivity.

The purpose of this paper is to report results of a study on using growth percent as an estimator of relative future productivity for trees in stands of old-growth timber growing on different forest ecosystem soils. The tree species included were Alaska-cedar (*Chamaecyparis nootkatensis* (D. Don) Spach), mountain hemlock (*Tsuga mertensiana* (Bong.) Carr.), Sitka spruce (*Picea sitchensis* (Bong.) Carr.), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and western redcedar (*Thuja plicata* Donn ex D. Don).

Study Area

The study area was the forested area of southeastern Alaska (fig. 1) from near Skagway in the north to Dixon Entrance in the south. The eastern boundary was the border between the United States and Canada, and the western boundary was the Pacific Ocean.

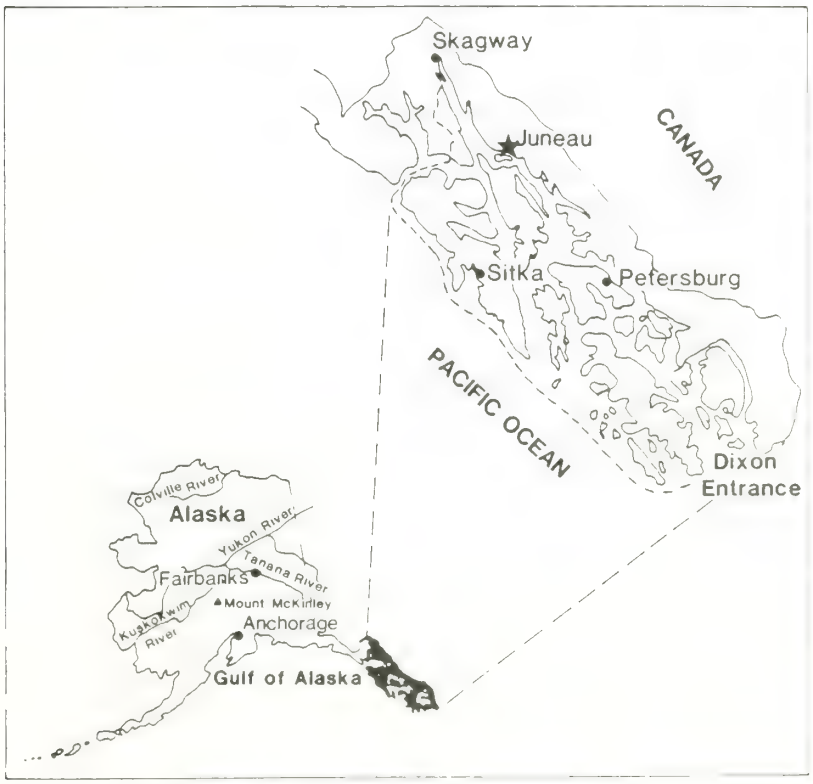


Figure 1—Study area in southeastern Alaska.

Objectives

This study was conducted to evaluate the use of periodic annual cubic-foot volume-growth percent (Pv) as a relative measure of timber productivity on different forest ecosystems in southeastern Alaska.

Volume growth was chosen (instead of diameter or basal area growth) to measure timber productivity because it incorporates growth in diameter and height. Estimates of volume growth are also directly usable in timber-growth models such as TRAS (Alig and others 1982).

Methods

Regression analysis was used to examine the relation between Pv, tree diameter at breast height (DBH), aspect, and percentage of live-tree stocking (LTS) on the sample plot for each tree species and forest ecosystem combination for which there were 30 or more observations. Five tree species on seven forest ecosystems were examined. Analysis of covariance was used to determine if individual equations for each species-ecosystem combination were in fact unique (Neter and Wasserman 1974). F-tests were performed on species equations within and between ecosystems.

Data

Data for this study were from forest resource inventories of southeastern Alaska done from 1970 to 1974. The field portion of the inventory consisted of 962 ten-point, variable-radius (basal area factor = 62.5), 1-acre timberland plots. Observations of tree height and diameter were made on each plot, and increment cores were taken to estimate diameter growth. The forest ecosystem soil (see below) at each plot was also recorded.

The focus of this study was on growth of individual trees. Total stand growth was not determined. To remove effects of age, disease, insect damage, and other physical causes of tree defect from the analysis, only those trees classed as "desirable" (see "Glossary") were selected.

Forest Ecosystems

The ecosystem classes used in this study were those in the forest ecosystem classification developed by Stephens and others (1969). They grouped standard United States Department of Agriculture (USDA) Soil Conservation Service soil series classifications into broader ecosystem categories based primarily on elevation, soil drainage, and soil depth. Further refinement was based on similarities in soil texture, development, and structure. A list of the soil series included in each major ecosystem is included in the glossary.

Dependent Variable

The dependent variable, Pv, is the ratio of periodic annual cubic-foot volume increment during the previous decade to tree volume at the beginning of the year prior to measurement, in percent. Periodic annual cubic-foot tree-volume increment was subtracted from current volume to obtain an estimate of the previous year's tree volume. Thus, Pv is an estimate of tree-growth percent during the year before measurement.

A measure of diameter growth and an estimate of height growth were needed to estimate Pv. Ten-year diameter increment was measured from a single increment core taken at breast height on the uphill side of the tree. The increment was divided by 10 to obtain an estimate of mean annual diameter increment.

Table 1—Cubic-foot volume equations used for the timber resource inventories of southeastern Alaska, 1970-74

Species	Volume equation[a]	Source
Sitka spruce:		
Poletimber	$V = 0.0022D^2H_T - 7.32683/D^2$	Embry and Haack 1965
Young-growth sawtimber	$V = 0.048534D^2H_L + 507.72/D^2$	Embry and Haack 1965
Old-growth sawtimber	$V = 16.30566 - 3.09606H_L + 0.04983D^2H_L$	Bones 1968
Western and mountain hemlock:		
Poletimber	$V = -2.85632 + 0.0633H_T + 0.00202D^2H_T$	Embry and Haack 1965
Young-growth sawtimber	$V = 5.2132 + 0.045805D^2H_L$	Embry and Haack 1965
Old-growth sawtimber	$V = 0.04915D^2 + 0.03912D^2H_L + 269.92685/D^2$	Bones 1968
Alaska-cedar:		
Poletimber	$V = 0.0316H_T + 0.001911D^2H_T - 28.78/D^2$	Farr and LaBau 1971
All sawtimber	$V = 2.0180H_L + 0.040236D^2H_L$	Farr and LaBau 1971
Western redcedar:		
Poletimber	$V = 0.04578D^2 + 0.001266D^2H_T - 27.17/D^2$	Farr and LaBau 1971
All sawtimber	$V = 0.5088D + 0.040668D^2H_L$	Farr and LaBau 1971

[a] V = cubic-foot volume (1-ft stump to 4-in top inside bark),
D = DBH,
H_T = total tree height, and
H_L = log height to a top diameter outside bark equal to 40 percent of DBH.

Height growth was estimated using an equation previously developed for use by the Forest Inventory and Analysis for Alaska (FIA) research unit in its ALCAL[1] program:

$$\text{HEIGHT GROWTH} = -0.454985 - 0.070728(\text{DBH}) + 0.192886\left(\frac{\text{SITE INDEX}}{10}\right);$$

where: HEIGHT GROWTH = annual growth in feet,
DBH = diameter at breast height in inches, and
SITE INDEX = estimate of plot site index.

Height growth as estimated with this equation was used to estimate total height at the end of the previous year. Tree volumes (current and 1 year ago) were estimated using species-specific volume equations relating tree volume to tree height and DBH (table 1).

Independent Variables

Aspect—Physical characteristics of forest sites, including slope, elevation, and aspect, affect tree growth. The ecosystem classification by Stephens and others (1969) is based, in part, on drainage (slope) and elevation. Because these variables are components of the ecosystem classification, they were not included as possible independent variables. Aspect was examined, however, for inclusion as an independent variable in regression. Sine and cosine transformations of aspect were evaluated along with sine and cosine transforms weighted by percentage of slope (Stage 1976).

[1] ALCAL is one of a series of software packages used to compile Forest Inventory and Analysis data. ALCAL is on file at the Forestry Sciences Laboratory, USDA Forest Service, 201 East Ninth Avenue, Suite 303, Anchorage, Alaska 99501.

Percentage of live tree stocking—The effect of stand density on tree growth is well known. The percentage of live-tree stocking (LTS) was used as a measure of the space available to live trees. The sum of LTS values for all individual trees on a plot was used to estimate stand density in the area around each sample tree.

The percentage of individual tree stocking was estimated by using the equation:

$$\text{Stocking percent} = \frac{(\text{basal area factor})(100)}{(\text{basal area standard})(np)} \; ;$$

where: np = number of variable-radius sample points in the ground plot; and
basal area standard = the tree spacing, expressed as basal area per acre, needed to capture the full growth potential at a given age and site index.

It was assumed that 60 percent of the normal yield-table basal-area stocking values for western hemlock and Sitka spruce (Taylor 1934) would provide a satisfactory estimate of full stocking and would serve as the basal area standard in computing LTS.

DBH—Both DBH and DBH^2 were tested for inclusion in the volume growth prediction equations. Tree age was not used because age was not available for all trees in this study.

Equation Form

Volume growth percent was expected to decrease curvilinearly for increases in LTS and DBH. A reciprocal function was used to express this relation. The equation form tested was:

$$Pv = a(\text{aspect}) + b\left(\frac{1}{LTS}\right) + c\left(\frac{1}{LTS^2}\right) + d\left(\frac{1}{DBH}\right) + e\left(\frac{1}{DBH^2}\right) \; ;$$

where: a, b, c, d, e = regression coefficients.

Results and Discussion

Equations and Tests of Significance

Regression analysis produced equations for 22 combinations of species and ecosystems. Analysis of covariance showed most equations to be unique. The final equations are shown in tables 2 and 3. Differences in Pv are evident both within and between soil groups. Ecosystems F2r and F5 show lower values of Pv than do the other ecosystems. Within ecosystems, the greatest difference in estimates of Pv between species occurs on F2 soils. With the exception of Alaska-cedar, mountain hemlock, and western hemlock on F2r soils, and Alaska-cedar and western hemlock on F5 soils, all equations within and between ecosystems were found to be significantly different from each other (where models were similar). Dissimilar models could not be tested against each other and were assumed unique.

Table 2—Regression equations of Pv for desirable trees growing on the F1, F2, and F4 forest ecosystems, by species, southeastern Alaska

Forest ecosystem and tree species	Regression equation	Number of trees	r^2	s e
F1:				
Sitka spruce	$Pv = -0.008 + 64.705(1/LTS) - 1977.936(1/LTS^2) + 461.279(1/DBH^2)$	244	0.801	0.69
Western hemlock	$Pv = -0.308 + 108.005(1/LTS) - 8635.503(1/LTS^2) + 535.278(1/DBH^2)$	424	.809	1.17
F2:				
Alaska-cedar	$Pv = -0.21 + 351.69(1/LTS) - 44567.148(1/LTS^2) + 218.692(1/DBH^2)$	48	.688	.55
Sitka spruce	$Pv = -0.164 + 21.633(1/DBH) + 67.225(1/DBH^2)$	153	.768	.49
Western redcedar	$Pv = -0.651 + 35.072(1/DBH)$	34	.813	.49
Western hemlock	$Pv = -0.987 + 229.156(1/LTS) - 14952.607(1/LTS^2) + 402.644(1/DBH^2)$	318	.709	1.32
Mountain hemlock	$Pv = -3.667 + 700.856(1/LTS) - 45186.505(1/LTS^2) + 783.045(1/DBH^2)$	57	.618	3.97
F4:				
Alaska-cedar	$Pv = -0.943 + 30.516(1/DBH) + 123.41(1/DBH^2)$	126	818	.68
Sitka spruce	$Pv = 0.240 + 218.736(1/DBH^2)$	156	640	.48
Western redcedar	$Pv = -0.618 + 38.004(1/DBH)$	90	.657	.63
Western hemlock	$Pv = -0.034 + 304.59(1/DBH^2)$	355	848	.69
Mountain hemlock	$Pv = -1.045 + 506.282(1/DBH^2)$	103	874	1.35

Table 3—Regression equations of Pv for desirable trees growing on the F5, F6, F2r, and f1 forest ecosystems by species, southeastern Alaska

Forest ecosystem and tree species	Regression equation	Number of trees	r^2	s e
F5:				
Alaska-cedar and western hemlock	$Pv = -0.487 + 74.072(1/LTS) - 3008.739(1/LTS^2) + 178.035(1/DBH^2)$	169	0.803	0.53
Sitka spruce	$Pv = -0.251 + 159.392(1/LTS) - 8020.865(1/LTS^2) + 98.981(1/DBH^2)$	40	.662	.50
Mountain hemlock	$Pv = 0.049 + 89.393(1/DBH^2)$	42	.676	.18
F6 Mountain hemlock	$Pv = -0.549 + 40.485(1/LTS) - 796.785(1/LTS^2) + 398.8(1/DBH^2)$	71	.926	.44
F2r:				
Alaska-cedar, western hemlock, and mountain hemlock	$Pv = -0.03 + 185.837(1/DBH^2)$	238	.811	.51
Sitka spruce	$Pv = 0.244 + 197.410(1/DBH^2)$	92	.649	.65
f1 Sitka spruce	$Pv = 0.588 + 54.810(1/DBH)$	59	.806	69

F2r soils consist of duff over bedrock and tend, at times, to become very dry. Western hemlock grows best on deep, internally well-drained soils; Alaska-cedar attains its best development near the upper elevational limits of merchantable timber where the soils are shallow to bedrock with groundwater seeping from higher elevations; and mountain hemlock shows its best development on loose, coarse-textured, well-drained, moist soils (Fowells 1965). The combined equation likely represents "poor" growth for western hemlock and mountain hemlock and "good" growth for Alaska-cedar.

F5 soils are essentially a duff layer over black muck or mucky peat, which in turn overlies sedge or sphagnum peat. The combined equation for Alaska-cedar and western hemlock represents generally poor growth of both species on these soils. A unique equation is needed to represent Sitka spruce growth on F5 soils probably because Sitka spruce grows well on soils high in organic matter that often have heavy accumulations of raw humus or moss (Fowells 1965).

Table 4—Comparison of estimates of site index[a] (100 years) of Sitka spruce with values of Pv for Sitka spruce, by ecosystem and 5-in diameter class (% LTS = 150)

Forest ecosystem	Site index (100 years)	Diameter class (inches)				
		5	10	15	20	25
	Feet	- - - - - - - - - - *Pv* - - - - - - - - - -				
F1	152	19.7	5.0	2.4	1.5	1.1
F2	118	6.9	2.6	1.6	1.1	.8
F2r	89	8.1	2.2	1.1	.7	.6
F4	118	9.6	2.6	1.3	.8	.7
F5	73	4.6	1.4	.8	.6	.5
f1	150	11.6	6.1	4.2	3.3	2.7

[a]From Stephens and others 1968.

For Sitka spruce, the results of this study are consistent with estimates by Stephens and others (1968) of site index for each ecosystem. Table 4 shows those estimates of Sitka spruce site index by ecosystem along with estimates of Pv by 5-in diameter class. For 5-in trees on F2 and F2r soils, the Pv values do not rank the same as the site index values; however, these differences diminish in the larger diameter classes.

Responses of Variables

Aspect, hypothesized to be significantly related to Pv, did not have statistical significance in any of the regression equations. A number of factors may contribute to this: First, aspect, as measured in the inventories, was recorded to the nearest 15 degrees. Second, tree growth is influenced by a large number of daylight hours on all aspects during the growing season in Alaska, and this, in combination with a measure of aspect that may be insensitive, could result in nonsignificant relations between Pv and aspect.

Live-tree stocking was not retained in all equations for two reasons. The Student's t-value associated with the coefficient of the variable was low, and most importantly, inclusion resulted in a meaningless response surface. The ambiguity of response of LTS likely derives from two sources: an insufficient number of observations in some cases and an inadequate range in magnitude of the observations in other cases.

Limitations

Height growth—Use of a single equation to estimate height growth for all tree species is questionable. The equation used was developed for stands of young-growth western hemlock and Sitka spruce. Because stands of western hemlock and Sitka spruce, both mixed and pure, account for almost 76 percent of the timberland in southeastern Alaska and nearly 81 percent of the cubic-foot volume (van Hees 1988), bias introduced by using one height growth estimator is likely less noticeable in the context of a large-scale timber inventory than in the narrower scope of this study. Height-growth equations for species other than western hemlock and Sitka spruce in southeastern Alaska are lacking, so it is not possible to estimate bias created by using this equation.

Diameter increment—Single increment cores are likely not a sufficient sample for estimating diameter growth of individual trees. Trees measured in the inventory occurred on a variety of slopes and aspects, so sampling bias introduced by using only one core sample should have been minimized.

Tree growth versus stand growth—No attempt was made in this study to estimate stand volume growth. Estimates of Pv derived from measurements made on only desirable trees should more closely approximate potential productivity than if all trees, including damaged, rough, rotten, and cull trees, had been included in the analysis. Although these equations were not developed from data collected from trees growing in young, even-aged stands, they do provide a relative comparison of growth among species and ecosystems.

Although stand growth was not estimated, it is reasonable to assume that stand growth will differ among ecosystems in a manner similar to that found for individual trees.

Inventory data—Using a large timber inventory data base as the source of data for a study such as this presents problems. The inventories conducted in southeastern Alaska by FIA were designed to produce estimates of overall timberland area and volume within certain error limits. They were not specifically designed to provide data for studies of narrow scope.

All forest ecosystems were sampled, but no control on sample size (number of trees) by ecosystem was exercised in design of the inventory. For this reason, only those species-ecosystem combinations for which there were at least 30 observations were selected for analysis. Other species were sampled on ecosystems F6 and F1 for instance, but the number of observations tended to be low (generally less than 20).

Glossary

Desirable trees—Trees greater than 5.0 in DBH having no serious defects in quality to limit present or prospective use, having relatively high vigor, and hosting no pathogens that could result in death or serious deterioration before rotation age.

Ecosystems (from Stephens and others 1969)—

F1: Extensive, well- to moderately well-drained soils with at least 10 in of mineral soil over bedrock. They occur from sea level to about 1,500 ft elevation, vary widely in parent material, and are sandy loam to silt loam in texture. Soils series included in this category are Farragut, Gunnuch, Karta, Kupreanof, Liesnoi, Rynda, Salt Chuck, Sokolof, Tolstoi, Tuxekan, Ulloa, Tokeen, and Sarkar.

F2: Freely drained soils, generally less than 10 in deep, and shallow to bedrock. As with the F1 soils, these are found from sea level to 1,500 ft elevation, but there is generally no water table. Only one soil series is included in this category: Mosman.

F2r: Essentially a duff layer over bedrock. These soils tend to become drier than many other soils. Only one soil series is included in this category: McGilvery.

F4: Somewhat poorly drained soils that vary widely in parent material and generally overlie some type of drainage restriction. Soil textures range from sandy loam to silt loam, and usually a seeping water table is present within 18 inches of the duff layer. Soil series included in this category are Mitkof, Sloduc, and Wadleigh.

F5: These soils are extensive in southeastern Alaska. They have 3 in to 1 ft or more of duff over a layer of black muck or mucky peat, which in turn usually overlies a layer of sedge or sphagnum peat. These soils usually have a water table within 1 ft of the base of the duff layer. Soil series included in this category are Kaikli, Karheen, and Maybeso.

F6: These soils are stony, somewhat poorly drained, and occur just under the alpine zone between 1,500 and 2,000 ft elevation. The soils are generally shallow to bedrock and rock outcrops are common. Only one soil series is included in this category: St. Nicholas.

f1: These soils are young, immature, alluvial soils and occur up to about 1,000 ft elevation. The soils lack well-developed horizons and have relatively thin O-horizons. Beneath the O-horizon is 8-30 in of dark brown silt loam to fine sandy loam, which overlies several feet or more of grayish, stratified gravels and sands. Only one soil series is included in this category: Tonowek.

Old-growth sawtimber trees—Live trees at least 11.0 in DBH and at least 150 yr old.

Poletimber trees—Live trees 5.0-10.9 in DBH.

Timberland—Forest land producing, or capable of producing, crops of industrial wood and not withdrawn from timber utilization. Areas qualifying as timberland can produce in excess of 20 ft^3/acre per year of industrial wood, under management. In old-growth stands along coastal Alaska, this is equated to stands that can produce 8,000 bd ft/acre (net International 1/4-in rule).

Young-growth sawtimber trees—Live trees at least 11.0 in DBH and less than 150 years old.

Literature Cited

Alig, Ralph J.; Brink, Glen E.; Goforth, Marcus H. [and others]. 1982. TRAS 1980: user's manual for an expanded version of the TRAS projection system. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 63 p.

Bones, James T. 1968. Volume tables and equations for old-growth western hemlock and Sitka spruce in southeast Alaska. Res. Note PNW-91. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 11 p.

Embry, Robert S.; Haack, Paul M. 1965. Volume tables and equations for young-growth western hemlock and Sitka spruce in southeast Alaska. Res. Note NOR-12. Juneau, AK: U.S. Department of Agriculture, Forest Service, Northern Forest Experiment Station. 21 p.

Farr, Wilbur A.; LaBau, Vernon J. 1971. Volume tables and equations for old-growth western redcedar and Alaska-cedar in southeast Alaska. Res. Note PNW-167. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 18 p.

Fowells, H.A., comp. 1965. Silvics of forest trees of the United States. Agric. Handb. 271. Washington, DC: U.S. Department of Agriculture. 72 p.

Neter, J.; Wasserman W. 1974. Applied linear statistical models. Homewood, IL: Richard D. Irwin, Inc. 842 p.

Stage, Albert R. 1976. An expression for the effect of aspect, slope, and habitat type on tree growth. Forest Science. 22(4):457-460.

Stephens, F.R.; Gass, C.R.; Billings, R.F. 1968. Soils and site index in southeast Alaska. Report No. 2 of the Soil-Site Index Administrative Study. Juneau, AK: U.S. Department of Agriculture, Forest Service. 3 p.

Stephens, F.R.; Gass, C.R.; Billings, R.F.; Paulson, D.E. 1969. Soils and associated ecosystems of the Tongass. Draft. Juneau, AK: U.S. Department of Agriculture, Forest Service. 139 p.

Taylor, R.F. 1934. Yield of second-growth western hemlock-sitka spruce stands in southeastern Alaska. Tech. Bull. 412. Washington, DC: U.S. Department of Agriculture. 30 p.

van Hees, Willem W.S. 1988. Effects of recent national legislation on ownership of timber resources in southeast Alaska. Res. Note PNW-RN-469. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 12 p.

van Hees, Willem W.S. 1988. Timber productivity of seven forest ecosystems in southeastern Alaska. Res. Pap. PNW-RP-391. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 10 p.

Observations of growth on Alaska-cedar (*Chamaecyparis nootkatensis*), mountain hemlock (*Tsuga mertensiana*), Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), and western redcedar (*Thuja plicata*) on seven forest ecosystems in southeastern Alaska were used to develop equations relating periodic annual cubic-foot volume growth percent (Pv) to tree diameter at breast height and percentage of live-tree stocking. Results showed differences in productivity between and within forest ecosystem soil groups.

Keywords: Soil productivity, growth rate, growth (plant) -)soil, Alaska (southeast).

The **Forest Service** of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives—as directed by Congress—to provide increasingly greater service to a growing Nation.

The U.S. Department of Agriculture is an Equal Opportunity Employer. Applicants for all Department programs will be given equal consideration without regard to age, race, color, sex, religion, or national origin.

Pacific Northwest Research Station
319 S.W. Pine St.
P.O. Box 3890
Portland, Oregon 97208

March 1988

U.S. Department of Agriculture
Pacific Northwest Research Station
319 S.W. Pine Street
P.O. Box 3890
Portland, Oregon 97208

BULK RATE
POSTAGE +
FEES PAID
USDA-FS
PERMIT No. G-40

Official Business
Penalty for Private Use, $300

do NOT detach label

GPO 592-973/80086

United States
Department of
Agriculture

Forest Service

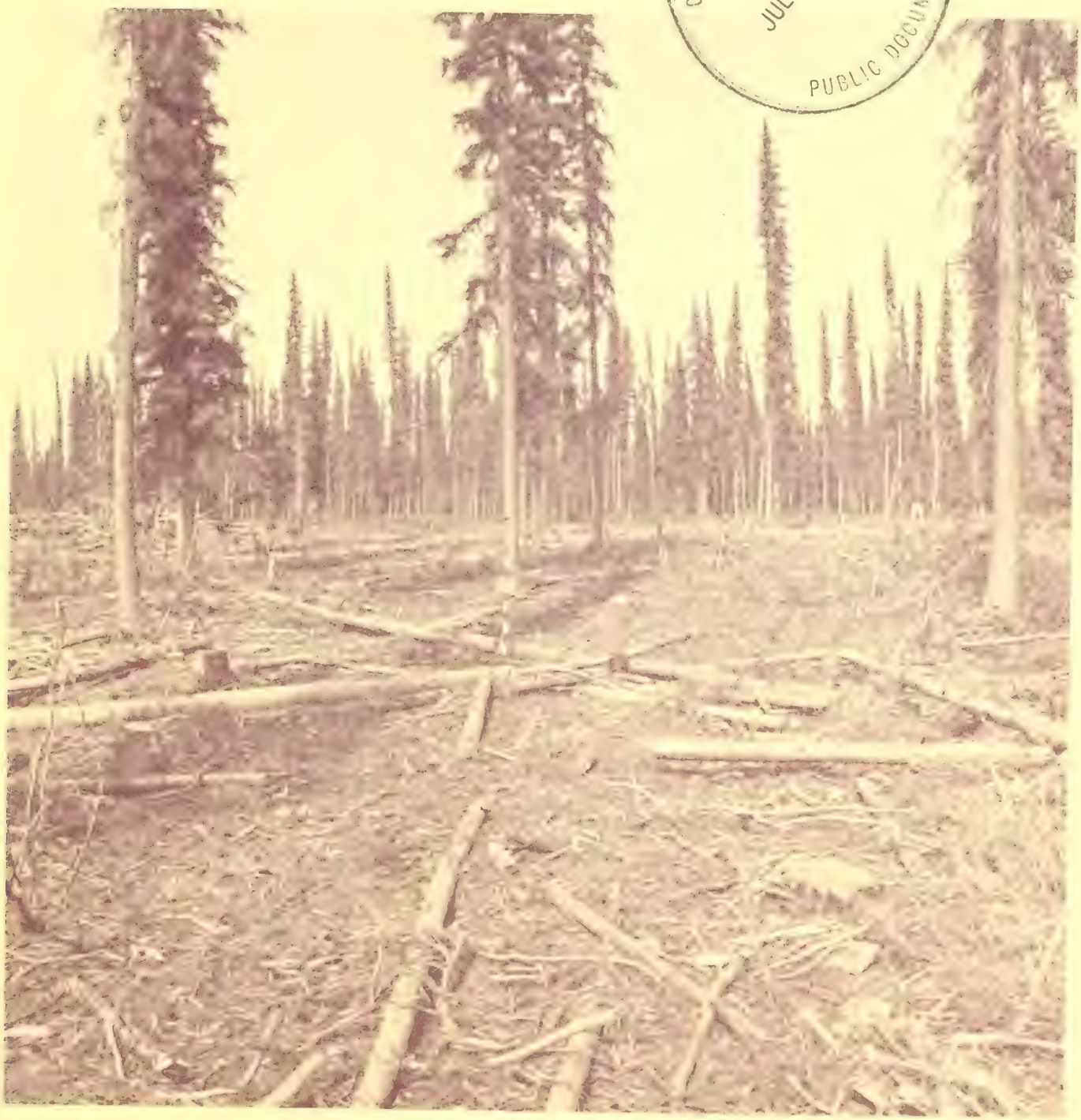
Pacific Northwest
Research Station

Research Paper
PNW-RP-392

The Effect on Vegetation and Soil Temperature of Logging Flood-Plain White Spruce

C.T. Dyrness, L.A. Viereck, M.J. Foote, and J.C. Zasada

CLEMSON UNIVERSITY
JUL 1988
PUBLIC DOCUMENTS



Authors

C.T. DYRNESS is a research soil scientist, L.A. VIERECK is principal plant ecologist, and M.J. FOOTE is a botanist, Institute of Northern Forestry, 308 Tanana Drive, Fairbanks, Alaska 99775-5500. J.C. ZASADA is a silviculturist, Forestry Sciences Laboratory, 3200 Jefferson Way, Corvallis, Oregon 97331.

Abstract

Dyrness, C.T.; Viereck, L.A.; Foote, M.J.; Zasada, J.C. 1988. The effect on vegetation and soil temperature of logging flood-plain white spruce. Res. Pap. PNW-RP-392. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station; 45 p.

During winter 1982-83, five silvicultural treatments were applied on Willow Island (near Fairbanks, Alaska): two types of shelterwood cuttings, a clearcutting, a clearcutting with broadcast slash burning, and a thinning. The effects of these treatments on vegetation, soil temperature, and frost depth were followed from 1983 through 1985. In 1984 and 1985, logged plots had significantly higher soil temperatures than did the controls; clearcut and burned sites had the greatest increases. Vegetation composition was profoundly changed on the clearcut and burned units and altered to a lesser extent on the units receiving the other treatments.

Keywords: Alaska, succession, forest communities, site preparation, soil series.

Summary

This study was conducted on Willow Island, a 200-ha island in the Tanana River, near Fairbanks, Alaska. Undisturbed soil and vegetation units were studied before silvicultural treatments were applied. Two soil series were identified and described: (1) Salchaket silt loam, a deep, well-drained alluvial soil lacking continuous permafrost; and (2) Tanana silt loam, which is characterized by impeded drainage resulting from shallow, continuous permafrost. Vegetation consisted mainly of mature white spruce forest, and 13 separate vegetation units were described. By far the most abundant forest communities were open *Picea glauca/Alnus tenuifolia/Hylocomium splendens*, open *Picea glauca/Alnus crispa-A. tenuifolia/Vaccinium vitis-idaea/ Hylocomium splendens,* and closed *Picea glauca/Alnus tenuifolia/Hylocomium splendens.* During winter 1982-83, five silvicultural treatments were applied to 79 ha: two types of shelterwood cuttings, a clearcutting, a clearcutting with burning, and a thinning. The effects of these treatments on vegetation and soil temperature and on frost depth were followed from 1983 through 1985.

Clearcutting followed by broadcast slash burning resulted in the most marked changes in vegetation and soil temperature. Many of the predisturbance species dropped out, and the posttreatment vegetation was dominated by invading species (*Populus tremuloides, Ceratadon purpureus*, and *Epilobium angustifolium*) and deep-rooted species (*Equisetum arvense* and *Rosa acicularis*). In one plot where permafrost had been present before clearcutting and burning, soil temperatures at the 10-cm depth were almost twice as high as they were in a nearby undisturbed control; all frost had completely left the soil. Clearcutting without burning diminished the impact on the site.

Many of the plant species originally in the understory survived the logging treatments. Because of remaining insulation provided by the forest floor and vegetative cover, soil temperature increases on clearcut sites (although still appreciable) were less than one-half those measured in areas clearcut and burned. The effects of the shelterwood treatments on the vegetation were minimal. Only three shade-loving species (*Goodyera repens, Calypso bulbosa,* and *Cypripedium passerinum*) dropped out of the stand. Shelterwood cutting resulted in significant increases in soil temperatures that were roughly comparable to those measured in the clearcut areas. The thinning treatments appeared to have the least impact on vegetation, and soil temperatures increased only slightly.

Contents

1 **Introduction**
1 Study Area
2 Silvicultural Treatments
2 **Methods**
2 Soil and Vegetation Reconnaissance and Mapping
4 Monitoring Soil Temperature and Frost
4 Vegetation Monitoring
6 **Results and Discussion**
6 Soils of Willow Island
7 Vegetation of Willow Island
11 Effects of Logging Treatments on Soil Temperature
18 Effects of Logging Treatment on the Natural Vegetation
41 **Conclusions**
43 **Acknowledgments**
43 **References**

Introduction

Flood plains are extensive in interior Alaska and, in later stages of succession, support productive stands of white spruce (*Picea glauca* (Moench) Voss). The successional sequence leading to white spruce has been studied and described in some detail (Krasny 1986, Krasny and others 1984, Van Cleve and others 1980, Van Cleve and Viereck 1981, Viereck 1970, Walker and others 1986). The main stages of interior Alaska flood-plain succession are pioneer willows (*Salix* spp.) and herbs, dense stands of willow and alder (*Alnus* spp.), balsam poplar (*Populus balsamifera* L.) and alder with white spruce in the understory, and white spruce/feathermoss. On some sites, black spruce (*Picea mariana* (Mill.) B.S.P.) replaces white spruce when the forest floor builds up so much that the soil cools and permafrost enters the profile.

Despite Alaska flood plains offering productive sites for the growth of white spruce, very little is known about managing these stands, especially about obtaining adequate amounts of forest regeneration after harvesting. Early studies indicated that factors controlling regeneration are distinctly different on flood plains vs. upland sites. Ganns (1977) studied artificial seeding of white spruce on a clearcut site next to the Tanana River. Seedlings germinated and became established on bare mineral seedbeds, but many seedlings exhibited symptoms of nutrient deficiencies. A considerable number of the young seedlings died, and it was thought that the prime mortality factors were high soil temperatures and soil drought. Putman and Zasada (1986) observed that germination and early survival occurred on both mineral soil and organic seedbeds, but mineral soil surfaces were best for early establishment.

To learn more about the ecology and management of Alaska white spruce on flood plains, an extensive cooperative study was begun in 1981. Willow Island was selected as the study site because it contained white spruce stands suitable for large-scale silvicultural manipulations.

The Willow Island study had two overall objectives:

1. To determine the requirements for natural and artificial regeneration and demonstrate management alternatives for white spruce on interior Alaska flood plains.

2. To quantify the effects of forest harvesting on flood-plain vegetation and soils.

This paper is a preliminary report of research results dealing with objective 2.

Study Area

The study was done on Willow Island, a 200-ha island in the Tanana River flood plain, about 30 km southwest of Fairbanks, Alaska. Almost the entire island is occupied by white spruce forest of varying age and density. The topography is essentially level, although several terraces occur, each representing a different age of alluvial deposition. Juday and Zasada (1984) describe the structure of six typical stands of white spruce on Willow Island that range from the first generation after balsam poplar to a stand in transition to black spruce. They found that the oldest land surfaces on the island are toward the east and west margins; the central portion is made up of lower and younger land surfaces. Juday and Zasada (1984) point out that soils with permafrost or intermittent frost are confined to the older land surfaces.

Silvicultural Treatments

Silvicultural treatments were carried out on about 79 ha. Five basic treatments were applied: shelterwood cuttings that left residual stands of two densities, a clearcutting, clearcutting with burning, and a thinning. All logging on the clearcut and shelterwood units was done during winter 1982-83. Because snow cover during logging was fairly deep, logging operations caused very little disturbance to the soil surface (Zasada and others 1987). The units were whole-tree logged; unmerchantable material was piled at the landing. Most of the branch material broke off during skidding and was distributed on the site. There were 2 shelterwood units with about 14-m residual tree spacing (37-62 trees per ha), 5 shelterwood units with 9-m spacing (85-100 trees per ha), 6 clearcuttings, 2 units clearcut and burned, 14 small thinned plots, and 5 unlogged control stands (fig. 1). Treatment units were spread over six forest community types but were predominant in two: open white spruce/mixed alder/cranberry/feathermoss (open *Picea glauca/Alnus/Vaccinium vitis-idaea/Hylocomium splendens*) and open white spruce/thinleaf alder/feathermoss (open *Picea glauca/Alnus/Hylocomium splendens*). Soils in treated areas were mostly two phases of the Salchaket soil series: deep phase and intermittent-frost phase.

Site preparation work, which included broadcast slash burning and mechanical scarification, was done during summer and fall 1983. On two clearcut units (12 and 16), the logging slash was broadcast burned in July 1983. The broadcast burning of the logging slash is described by Zasada and Norum (1986). Slash concentrations at landings were machine piled and burned. Parts of each shelterwood and clearcut unit were then patch scarified, blade scarified, or left unscarified as controls, and forest regeneration plots were established. Each logging unit has at least one set of plots for tree regeneration; larger units have several. Each set includes patch-scarified, blade-scarified, and unscarified areas. Forest regeneration treatments included spot sowing of seed and planting containerized white spruce seedlings.

Methods

The work reported here involved efforts in three distinct areas of study and was carried out from 1981 through 1985. The methods used in the three areas of study will be treated separately.

Soil and Vegetation Reconnaissance and Mapping

During summer 1981, while Willow Island was still completely undisturbed, a reconnaissance study was made of its soils and vegetation. The purpose was to describe the soil and vegetation units and to map their distribution before we began any treatments. Besides the observations made during traverses of the island, detailed soil and vegetation data were collected at about 30 representative locations.

At each location, a soil pit was excavated, and a complete soil profile description was made following procedures outlined in the "Soil Survey Manual" (Soil Survey Staff 1951). At selected locations, soil samples from each horizon were also collected. Measurements of frost depth were taken near each soil pit and randomly between sites by using a steel probe calibrated in centimeters.

At each sampling site the vegetation was also described by making visual estimates of cover for each species within a circular area about 20 m in radius around the soil pit. Tree canopy cover was estimated for a larger area to make that figure more representative. Stand age was approximated from ring counts of increment cores taken at breast height from representative trees at the sampling site.

Soil and vegetation maps were prepared on aerial photographs and then transferred to a planimetric base map. The mapping was done by using the information about each sampling site, comparisons among sites, and inferences made by noting changes in vegetation and landform on the photographs.

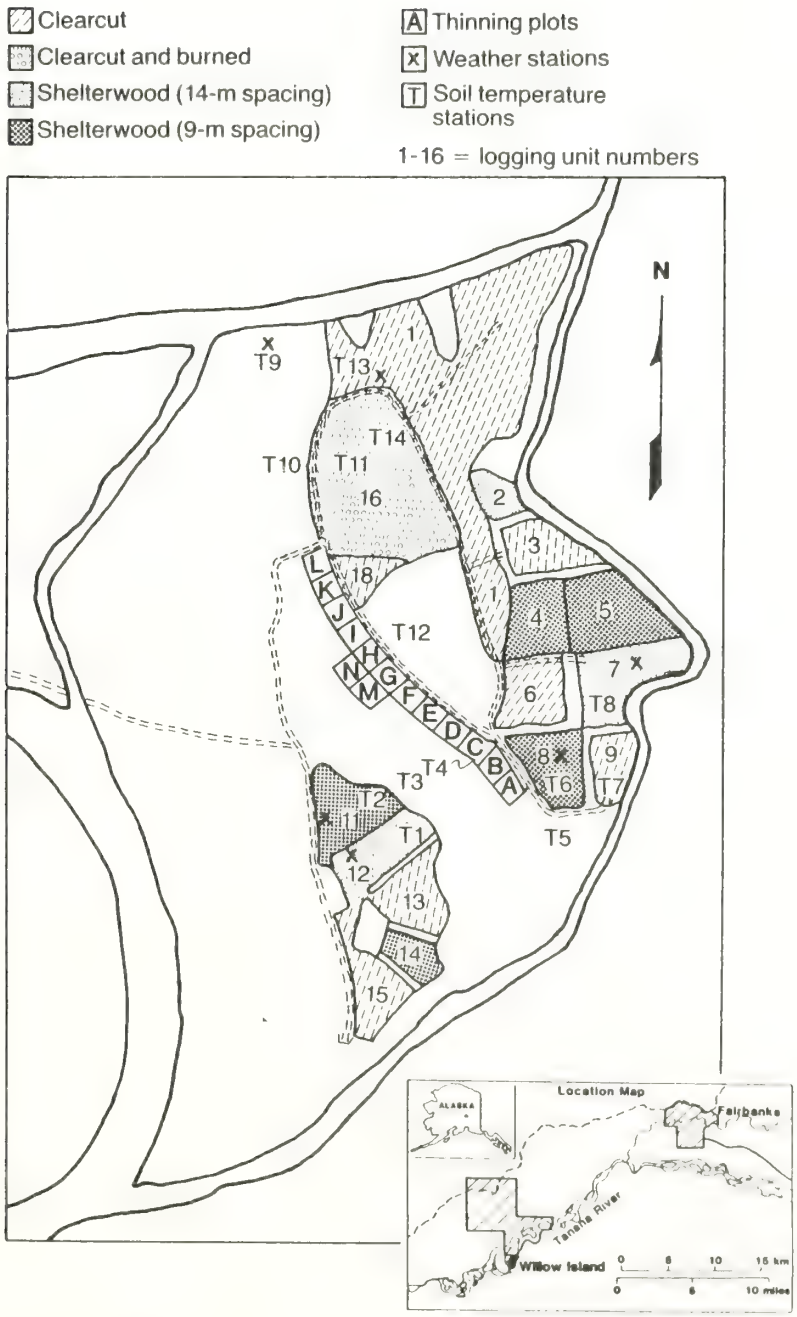


Figure 1—Willow Island with logging units and locations of soil-temperature plots shown.

Monitoring Soil Temperature and Frost

In 1982, before silvicultural treatments were applied, 12 stations were established for monitoring soil temperature and frost. Six plots were in undisturbed, control areas, and six were in areas scheduled for logging (three in shelterwoods and three in clearcuts) (table 1). In 1983 temperature plot 13 was added in a clearcut area, and in 1984 plot 14 was added in a clearcut and burned area. As indicated in figure 1 and table 1, plots were grouped into four clusters, each cluster having one to three silviculturally treated plots and a nearby control plot. Control plots were closely similar to the treated plots, both in vegetation and soil characteristics (table 1). One additional control, plot 9, was near the central climatic station.

During the summers of 1982 through 1985, soil temperatures and frost depths were measured weekly, beginning in late May and extending through mid-September. At each station, soil temperatures were measured at three locations and frost depths at eight locations along a transect. The sites for temperature measurement were permanently marked and were about 2 m apart along the transect. We used two Yellow Springs telethermometer probes, 15 and 90 cm long, to measure soil temperatures at depths of 5, 10, 20, and 50 cm. The probes were inserted vertically and allowed to come to temperature equilibrium with surrounding soil before the values were recorded. Measurements of frost depth were taken along the same transect by using a calibrated steel probe 2 m long. The middle three frost measurements were taken at the marked temperature locations. Frost-depth measurements were also taken at two points 2 m apart at one end of the transect, and at three points at 2-m intervals at the other end of the transect.

Most analyses of soil-temperature data were based on temperature degree-day summations. These soil degree-day accumulations were calculated for both the 10- and the 20-cm depths, with 0 °C as the base, for May 25 to September 15. Analyses of variance were done for these degree-day sums to determine the significance of treatment effects. To facilitate comparison of treatment means, Fischer's protected least significant difference values were calculated. Because of so few replications, all data for control, shelterwood, clearcut, and clearcut and burned plots were pooled for statistical analyses, rather than the analyses being performed on the three separate plot clusters (blocks). In other comparisons, differences between the treated plots and the undisturbed controls were based on the appropriate, paired control and not on pooled data.

Vegetation Monitoring

Twenty permanent vegetation plots were established in each of the 15 logging treatment units, in 5 control units, and in 2 of the 12 thinned units during or before summer 1982. The vegetation on these permanent plots was surveyed using techniques developed by Ohmann and Ream (1971) and Cottam and Curtis (1956), and modified by Foote (1983). The vegetation plots were sampled in 1982 before the logging treatments were begun, in 1983 immediately after treatments were completed, and at the end of the first two growing seasons. Plots in the two burned units were also monitored in 1985. The vegetation growing on these permanently marked plots will be surveyed at intermittent intervals to document the long-term effect of the treatments. These permanent plots are useful for measuring change introduced by the logging, site preparations, and regeneration treatments.

Table 1—Characteristics of logged soil-temperature plots and an associated unlogged control[a]

Treatment and soil-temperature plot number (in parentheses)	Soil unit	Vegetation type
Control (3)	Deep Salchaket	Open *Picea glauca/Alnus/Hylocomium*
Clearcut and burned (1)	Deep Salchaket	Open *Picea glauca/Alnus/Hylocomium*
Shelterwood, 9-m spacing (2)	Shallow Salchaket	Open *Picea glauca/Alnus/Hylocomium*
Control (5)	Salchaket with intermittent frost	Open *Picea glauca/Alnus/Vaccinium/ Hylocomium*
Clearcut (7)	Salchaket with intermittent frost	Open *Picea glauca/Alnus/Vaccinium/ Hylocomium*
Shelterwood, 9-m spacing (6)	Salchaket with intermittent frost	Open *Picea glauca/Alnus/Vaccinium/ Hylocomium*
Shelterwood, 14-m spacing (8)	Salchaket with intermittent frost	Open *Picea glauca/Alnus/Vaccinium/ Hylocomium*
Control (12)	Tanana	Woodland *Picea glauca/Ledum-Vaccinium/feathermoss*
Clearcut and burned (11)	Tanana	Woodland *Picea glauca/Ledum-Vaccinium/feathermoss*
Clearcut (13)[b]	Tanana	Woodland *Picea glauca/Ledum-Vaccinium*/feathermoss
Clearcut and burned (14)[c]	Tanana	Woodland *Picea glauca/Ledum-Vaccinium*/feathermoss
Control (10)	Deep Salchaket	Closed *Picea glauca/Alnus/Hylocomium*
Thinned (4)	Deep Salchaket	Closed *Picea glauca/Alnus/ Hylocomium*
Control (9)[d]	Deep Salchaket	Open *Picea glauca/Alnus/ Hylocomium*

[a] Location of the plots is shown in figure 1. Soil temperature and frost depth were measured from 1982 (before logging) through 1985 except plots 13 and 14.
[b] Plot added 1983.
[c] Plot added 1984.
[d] Not paired with any logged plot. Installed as a supplement to the main climatic station on Willow Island.

Results and Discussion

Soils of Willow Island

The alluvial soils of Willow Island are young and generally show little profile development. They formed in highly variable water-laid deposits of sand and silt. About 90 percent of the island has soils classified as belonging to the Salchaket soil series (Typic Cryofluvents). Salchaket soils are well drained and develop in alluvial deposits on generally level terraces and flood plains. Soil profiles typically exhibit several periods of alluvial deposition separated by organic horizons (buried forest floor layers). Three phases of the Salchaket soil were recognized and described: a deep phase, a shallow phase, and a phase with intermittent frost.

The deep phase of the Salchaket soil occupies at least two-thirds of the total area. These are soils with fine materials (sand and silt) that are at least 75 cm deep over water-worn gravels. In the shallow phase of the Salchaket, gravels are encountered within the top 25-75 cm. Deep Salchaket soils are characterized by forest floor layers varying from very thin (1-3 cm) to moderately thick (14-16 cm). The humus layer ranges from absent to 3 cm thick. Silt from recent floods is often intermixed with the forest floor material. The mineral soil is comprised of silt and sand-sized particles, and texture tends to become coarser with depth. A typical profile may have 20-40 cm of silt loam over horizons of very fine sandy loam that lie over layers of fine to medium sands. Roots are abundant near the surface, particularly in the organic layers, but decrease rapidly with depth.

The following is a generalized description of a profile typical of a deep Salchaket soil on Willow Island: 4-0 cm, recently deposited litter and feathermoss remains; 0-4 cm, grayish brown (10 YR 5/2)[1] silt loam, weak fine subangular blocky structure, very friable, roots abundant; 4-7 cm, very dark grayish brown (10 YR 3/2) organic material (buried forest floor layer), roots abundant; 7-19 cm, brown (10 YR 5/3) with mottles of light gray (10 YR 6/1) and yellowish brown (10 YR 5/6) silt loam, weak fine platy structure, friable, roots abundant; 19-24 cm, brown (10 YR 5/3) with scattered mottles of light gray (10 YR 6/1) silt loam with common lenses of organic material, weak medium subangular blocky structure, friable, roots abundant; 24-35 cm, brown (10 YR 5/3) with scattered mottles of light gray (10 YR 6/1) and yellowish brown (10 YR 5/6), fine sandy loam, very weak subangular blocky structure, very friable, roots common; 35-61 cm, grayish brown (10 YR 5/2) fine sand, single-grained, loose, few roots; 61-80 cm, grayish brown (10 YR 5/2) medium sand, single-grained, loose, scattered roots; and 80-100+ cm, grayish brown (2.5 Y 5/2) sands and water-worn gravels, roots very scattered.

The intermittent-frost phase of the Salchaket soil is similar to the deep phase in horizon characteristics except that lenses of ice are observed in the subsurface layers, usually at depths of 40-60 cm. Most often the layers of frozen soil are discontinuous and do not appear to occur in any pattern. Reiger and others (1963) also observed these frozen lenses in Salchaket soils and described them as "thin silty lenses that...stay frozen...long after the sandy strata have thawed." The ice content of the frozen layers is often low, and the layers can be punctured by a shovel or probe. By late summer, much of the frost has retreated to deeper layers or has completely left the profile.

The intermittent-frost phase of the Salchaket soil occupies about one-fifth of the total area of Willow Island and is restricted to the eastern side. These soils are characterized by forest floors 5-23 cm thick. Silt is commonly intermixed with the organic materials. At least a thin humus layer is generally present above the mineral soil. As in the deep phase of the Salchaket, textures of the surface mineral soil tend to be silt loams, with the soil becoming more coarse textured (sandier) with depth. A

[1] Munsell color notation for moist soil.

substratum of rounded gravels occurs at depths greater than 1 m. Roots are abundant in the forest floor and common to about the 10-cm depth in the mineral soil. Roots are also abundant in the buried organic layers common in these soils.

The shallow phase of the Salchaket soil is uncommon and occupies only 1-2 percent of the area in the interior of the island. The forest floor layer in these soils is thin to lacking. The mineral soil is generally a fine sand, and water-worn gravels are found at depths of 25-75 cm.

The Tanana soil series includes soils characterized by a shallow active layer and a continuous permafrost layer. They are classified as Pergelic Cryaquepts. Tanana soils occupy about 10 percent of the area and are located on a midisland terrace surrounded by abandoned sloughs. This terrace is farthest from the current river channel and presumably is the oldest landform on the island. Tanana soils are poorly drained and have silt loam surface textures that grade, with depth, into more coarsely textured soils. The forest floor is generally well developed and is 15-25 cm thick. Depth to permafrost is generally in the 50- to 70-cm range at the end of the growing season. Impeded drainage due to the permafrost table causes the soils under undisturbed vegetation to be wet throughout the growing season. Roots are abundant only in the forest floor and the top horizon of the mineral soil; poor soil drainage restricts deeper penetration.

The following is a generalized description of a soil typical of the Tanana series on Willow Island: 15-0 cm, recently deposited litter and partially decomposed moss remains; 0-5 cm, very dark grayish brown (10 YR 3/2) silt loam, weak granular structure, very friable, roots abundant; 5-10 cm, grayish brown (10 YR 5/2) with mottles of dark yellowish brown (10 YR 4/4) and brown (7.5 YR 4/4) fine sandy loam, weak fine subangular blocky structure, friable, roots scattered; 10-19 cm, dark grayish brown (2.5 Y 4/2) with scattered mottles of dark yellowish brown (10 YR 4/4) and gray (10 YR 5/1) loamy fine sand, weak very fine subangular blocky structure, friable, roots scattered; 19-37 cm, dark grayish brown (2.5 Y 4/2) with scattered mottles of yellowish brown (10 YR 5/4) loamy fine sand, weak fine subangular blocky structure, friable, roots very scattered; and 37 cm and deeper, ice-rich permafrost.

Vegetation of Willow Island

Thirteen vegetation mapping units were established based on reconnaissance plot data, additional field examination, and aerial photo interpretation. These mapping units are, for the most part, forest communities conforming to standards described in Viereck and others (1986). According to this classification, the canopy coverage of the tree layer is broken down as follows: woodland with 10-25 percent tree cover, open forest with 25-60 percent tree cover, and closed forest with 60-100 percent tree cover. The 13 communities mapped on Willow Island are described below, roughly in descending order of their abundance.

Open *Picea glauca/Alnus tenuifolia/Hylocomium splendens* (open white spruce/thinleaf alder/feathermoss)--This forest community occupies the largest area on Willow Island, about one-third of the island. It occurs primarily on the western half of the island on deep Salchaket soils. Tree overstory cover ranges from about 30 to 60 percent and is primarily white spruce. Balsam poplar often occurs as a very minor component in the overstory, and dead standing and down trees are commonly scattered throughout the stand. White spruce vary from 15 to 35 cm in diameter at breast height (d.b.h.) and range from 110 to 150 years old.

Alder cover is highly variable, ranging from about 10 to 80 percent. *Alnus tenuifolia* is by far the most common species, but *A. crispa* also occurs. Other tall shrub species include *Rosa acicularis* and *Viburnum edule* (Michx.) Raf. *Linnaea borealis* L. is the dominant low shrub; however, *Vaccinium vitis-idaea* is sometimes present in small quantities. *Geocaulon lividum* (Richards.) Fern. is the dominant herb (2-15 percent cover). Other common herbs are *Pyrola asarifolia* Michx. and *P. secunda* L. Herbs occurring in smaller quantities include *Carex* spp., *Hedysarum alpinum* L. subsp. *americanum* (Michx.) Fedtsch., *Equisetum arvense, E. scirpoides* Michx., and *Goodyera repens* (L.) R. Br. var. *ophioides* Fern. The moss layer is highly variable with the cover ranging from 15 to 95 percent. The dominant moss species is *Hylocomium splendens* (Hedw.) B.S.G., though *Pleurozium schreberi* (Brid.) Mitt., *Drepanocladus* sp., and *Eurhynchium* sp. are also common. Lichens, mostly *Peltigera* spp., are present but uncommon.

This community type was one of the major types used in this study and is represented by silvicultural treatment units 11 to 15 and soil temperature stations T1 through T3 (fig. 1).

Open *Picea glauca/Alnus crispa-A. tenuifolia/Vaccinium vitis-idaea/Hylocomium splendens* (open white spruce/mixed alder/lingonberry/feathermoss)–This forest community occupies about 25 percent of the total area and occurs exclusively on the northeast portion of island. It is associated with colder, generally wetter soils--the intermittent frost phase of the Salchaket and the Tanana soil series. The forest canopy, primarily white spruce, ranges from 30 to 50 percent in cover. The only other tree species is paper birch, which occurs in varying amounts. Average d.b.h. of white spruce is 20-40 cm, and ages range from 130 to over 350 years.

Alnus crispa and *A. tenuifolia* are the dominant tall shrubs with cover of 10-80 percent. Other commonly occurring shrubs include *Rosa acicularis* and *Viburnum edule*. The dominant species in the low shrub-herb layer is *Vaccinium vitis-idaea* (20-50 percent cover). *Linnaea borealis, Equisetum arvense, Cornus canadensis* L., and *Geocaulon lividum* are always present. Other herbs frequently occurring in smaller quantities include *E. scirpoides, Pyrola asarifolia, Calamagrostis canadensis* (Michx.) Beauv., *Hedysarum alpinum, Mertensia paniculata* (Ait.) G. Don, *P. secunda, Moneses uniflora* (L.) Gray, *Goodyera repens*, and *Carex* spp. This community has a luxuriant moss cover, primarily of *Hylocomium splendens*. Other moss species include *Pleurozium schreberi, Rhytidiadelphus triquetrus* (Hedw.) Warnst., *Dicranum fuscescens* Turn., *Eurhynchium* sp., *Drepanocladus* sp., and leafy liverworts, primarily *Ptilidium ciliare* (L.) Nees.

This type differs from the previously described open white spruce type primarily by being much older, by having *Alnus crispa* as well as *A. tenuifolia* in the shrub understory, and by having the colder wetter soils often associated with permafrost. Silvicultural treatment units 2 through 9 and soil temperature units T5 and T9 are in this type.

Closed *Picea glauca/Alnus tenuifolia/Hylocomium splendens* (closed white spruce/thinleaf alder/feathermoss)--This forest community occurs in several locations and occupies about 25 percent of the total area of the island. The associated soil is generally the deep phase of the Salchaket series. The overstory cover ranges from 55 to 70 percent and is mostly white spruce with minor amounts of balsam poplar and paper birch (*Betula papyrifera* Marsh.). Some scattered tamarack (*Larix laricina* (Du Roi) K. Koch) and black spruce are also present. White spruce trees are about 120-150 years old and 15-20 cm d.b.h.

Cover provided by alder, primarily *Alnus tenuifolia*, is highly variable and ranges from about 5 to 75 percent. As in the more open community described above, other, less abundant tall shrub species include *Rosa acicularis* and *Viburnum edule*. The low shrub-herb layer is generally poorly developed and made up of *Carex* spp., *Geocaulon lividum, Pyrola asarifolia, P. secunda, Linnaea borealis, Equisetum arvense*, and *Calamagrostis canadensis. Vaccinium vitis-idaea* may be present but provides less cover than does *L. borealis*. The moss layer is usually well developed (averaging 60-45 percent cover) and is mostly *Hylocomium splendens,* though *Dicranum* sp., *Drepanocladus* sp., and *Eurhynchium* sp. are present. The lichen layer is sparse and primarily composed of *Peltigera* lichens. This type differs from the open *Picea glauca/Alnus/Hylocomium splendens* type only in having a slightly more closed canopy, less *R. acicularis* and *L. borealis*, and fewer herbs.

A series of small thinning plots was established in this type (units A-L), and two soil temperature stations (T4 and a control T10) were used to look at the effects on soil temperatures of one of the thinning treatments.

Open *Picea glauca/Alnus tenuifolia/Calamagrostis-Vaccinium vitis-idaea* (open white spruce/thinleaf alder/bluestem-lingonberry)--This community is characterized by an open stand of predominantly young white spruce. It occupies about 5 percent of the area of Willow Island and is centered in the western portion of the island where selective logging was done about 50 years ago. Associated soils are mostly deep Salchaket and Tanana. White spruce, 30-50 years old and 10 cm d.b.h., is the major tree component. Paper birch is generally present and may contribute up to one-third of the total canopy. Tree canopy coverage ranges from 30 to 60 percent.

Alder is the dominant shrub (30-45 percent cover). Other common tall shrubs are *Salix* spp., *Rosa acicularis, Viburnum edule*, and *Ledum groenlandicum* Oeder. The herb and low shrub layer is well developed with an average cover of about 70 percent. The dominant species are *Calamagrostis canadensis, Vaccinium vitis-idaea,* and *Equisetum arvense*. Other herbs present in smaller quantities are *Linnaea borealis, Geocaulon lividum, Carex* spp., *Cornus canadensis,* and *Epilobium angustifolium* L. The moss layer is open (15-30 percent cover) and predominantly *Hylocomium splendens.*

Open *Picea glauca/Alnus tenuifolia* (open white spruce/thinleaf alder)--This community is open stands of young white spruce with poorly developed herb layers. It is found on 5 percent of the area and on deep Salchaket soils on the western side of the island. Spruce cover ranges from 25 to 60 percent and is made up of small (15 cm d.b.h.) and young (40 years) trees. Scattered older balsam poplar are sometimes encountered.

The most common tall shrubs (10-50 percent cover) are *Alnus tenuifolia, Salix alaxensis* (Anderss.) Cov., and *Rosa acicularis*. The sparse herb layer is dominated by *Geocaulon lividum, Calamagrostis canadensis*, and *Equisetum arvense*. Other common species are *Pyrola asarifolia*. Mosses and lichens are not abundant in this community.

Closed tall *Salix* (closed tall willow)--This dense willow community occurs on the flood plain immediately adjacent to the river along all margins of the island. The width of this band varies, but in most locations it is only a few meters across. The community makes up about 2.5 percent of the island's area. The dense shrub cover is primarily *Salix* spp., but some *Alnus tenuifolia* may be present. The herb layer is scattered and mainly *Equisetum* spp.

Woodland *Picea glauca/Ledum groenlandicum-Vaccinium vitis-idaea*/feather-moss (woodland white spruce/Labrador tea-lingonberry/feathermoss)--This community occurs on the oldest land surface in the center of the island on the Tanana soil characterized by shallow permafrost. It occupies about 2 percent of the total area. The tree overstory is open and usually provides only 15-20 percent cover. Although white spruce is dominant, black spruce is common (up to one-third of the stand); paper birch also occurs. Both white spruce and black spruce have an average d.b.h. of 20 cm. White spruce is about 200 years old, and the black spruce is about 130 years old. The many remains of large trees on the ground suggest that present stands may be the second or even third generation.

The tall shrub layer is sparse and mostly *Salix* spp. and *Rosa acicularis*. Low shrubs are abundant, however, with *Ledum groenlandicum* and *Vaccinium vitis-idaea* being dominant. *Empetrum nigrum* L., *Linnaea borealis*, and *V. uliginosum* L. also occur in smaller quantities. Common herbs are *Equisetum arvense, Geocaulon lividum*, and *Cornus canadensis*, though *Calamagrostis canadensis, E. scirpoides, Lycopodium annotinum* L., and *Pyrola secunda* also occur. Moss cover is well developed and averages 60-70 percent. Dominant species are *Hylocomium splendens* and *Pleurozium schreberi.* Minor components are *Dicranum fuscescens, Sphagnum* spp., *Drepanocladus* sp., and leafy liverworts, primarily *Ptilidium ciliare.* Lichen cover averages 15-35 percent and is predominantly *Peltigera aphthosa* (L.) Willd., though *P. canina* (L.) Willd., *Cetraria islandica* (L.) Ach., and several *Cladonia* species (*C. amauocraea* (Flörke) Schaer., *C. gracilis* (L.) Willd., *C. rangiferina* (L.) Web., and *C. sylvatica* (L.) Hoffm.) occur.

This woodland type was represented in this study by a large clearcutting (units 1 and 16), much of which was also burned (unit 16) and by soil temperature units T11 through T14 (fig. 1).

Closed *Populus balsamifera/Alnus tenuifolia/Equisetum* (closed balsam poplar/thinleaf alder/horsetail)--This forest community is of limited extent and is confined to the western portion of the island on deep Salchaket soils. The stands are fairly dense with an average canopy coverage of about 75 percent. White spruce is also generally present in the understory. Balsam poplar age is about 60-80 years. The tall shrub layer is dominated by *Alnus tenuifolia* and has smaller quantities of *Salix novae-angliae* Anderss., *Rosa acicularis*, and *Viburnum edule.* The herb layer is dominated by *Equisetum arvense; Geocaulon lividum* is also common. Species present in smaller quantities include *Hedysarum alpinum, Cornus canadensis, Calamagrostis canadensis, Epilobium angustifolium, Linnaea borealis,* and *Pyrola asarifolia.* The ground cover is mostly leaf litter with only traces of feathermoss.

Closed *Picea glauca/Equisetum/Hylocomium* (closed white spruce/horsetail/ feathermoss)--These stands are mostly small white spruce, which are closely spaced and occur near the eastern margin of the island (less than 1 percent of the total area). The type occurs on the intermittent frost phase of the Salchaket soil. The trees are 10-20 cm d.b.h. and their average age is about 130 years. Alder is absent from this community, unlike most of the island communities, and the only tall shrubs are scattered *Rosa acicularis and Viburnum edule.* The herb layer is marked by a luxuriant cover of *Equisetum arvense* (up to 75 percent cover). Other herbs present in small amounts include *Vaccinium vitis-idaea, Cornus canadensis, Linnaea borealis, Geocaulon lividum, Mertensia paniculata,* and *Pyrola asarifolia.* Mosses are dense and luxuriant (90 percent cover). The dominant species is *Hylocomium splendens;* however, *Pleurozium schreberi, Rhytidiadelphus triquetrus*, and *Dicranum fuscescens* are also present.

Woodland *Picea glauca/Alnus tenuifolia/Arctostaphylos uva-ursi*/lichen (woodland white spruce/thinleaf alder/bearberry/lichen)--Although the distribution of this community is limited, it is unlike any other on the island. It is located in the middle of the island on the shallow phase of the Salchaket soil. The white spruce overstory is very open, averaging perhaps 25 percent cover. The tall shrub layer is also quite open and consists of *Alnus tenuifolia* and *Salix* spp. The herb and low shrub layer is sparse and is dominated by patches of *Arctostaphylos uva-ursi* (L.) Spreng. *Hedysarum alpinum* is also present in small amounts. Mosses are scattered and mostly *Polytrichum* spp. Lichens provide the most abundant cover in this unit. Lichens identified are *Stereocaulon* spp., *Cladonia gracilis, C. alpestris* (L). Rabenh., and *C. sylvatica.*

Abandoned sloughs--Abandoned water channels are abundant on the island but have not been adequately described. Some are only slightly noticeable as depressions, but others are wide and deep. White spruce occurs in a few of the sloughs, but alder is more common. Sweetgale (*Myrica gale* L.) is an occasional low shrub. In most of the sloughs, herbaceous species provide most of the cover. Grasses, sedges, iris (*Iris setosa* Pall.), and some composites make up most of the cover. When the river stage is high, most sloughs become ternporarily flooded.

Closed *Picea glauca/Alnus crispa-A. tenuifolia/Vaccinium vitis-idaea/Hylocomium splendens* (closed white spruce/mixed alder/lingonberry/feathermoss)--This type differs from the open *Picea glauca/Alnus crispa-A. tenuifolia/Vaccinium vitis-idaea/Hylocomium splendens* type previously described in that the tree canopy is more closed; the alder has a little less cover; and *Vaccinium vitis-idaea, Linnaea borealis,* and *Hylocomium splendens* tend to have greater cover.

Open *Picea glauca/Hylocomium splendens* (open white spruce/feathermoss)--Stands of this type occasionally occur near sloughs or along the edge of the island. Tree size and age vary. In some stands, they are 20-34 cm d.b.h. and 150-210 years old; in other stands, the d.b.h. is 6-27 cm and the age is about 115 years. Alder has low cover. The shrub layers, both tall and low, and the herb layer are poorly developed, each covering less than 15 percent of the forest floor. *Rosa acicularis* and *Viburnum edule* dominate the tall shrub layer; *Linnaea borealis, Geocaulon lividum,* and *Equisetum arvense* are most abundant in the low shrub and herb layer. The moss layer, which is well developed, is dominated by *Hylocomium splendens* and *Rhytidiadelphus triquetrus.* Lichens, primarily *Peltigera* and a few *Cladonia* growing on mineral soil, occur but are not common.

Effects of Logging Treatments on Soil Temperature

We had the unusual opportunity to compare soil temperatures on control plots and treated plots before treatments were applied in 1983. We used soil degree-days for the entire measurement period as the basis of comparison; correlation of temperatures at a depth of 10 cm between the control plots and plots destined to have treatments was quite good (table 2). With the exception of plot 8, agreement was within ± 15 percent in 1982 before treatment. Soil temperatures at plot 8, even before treatment, were considerably warmer than those in the control plot. At a depth of 20 cm, differences in soil temperature in 1982 between the control and plots to be treated were greater (table 3). Once again, by far the largest difference was between the control and plot 8, where it was almost 60 percent. The reason for this difference between temperature variation at 10 and 20 cm is obscure; temperature uniformity usually increases with soil depth.

Table 2—Soil degree-day values at the 10-cm depth for the 16-week growing season (last week in May to mid-September) in 1982 (before logging) and the first 3 years after logging (1983-85) by logging treatment, soil-temperature plot, and site preparation[a]

Logging treatment soil-temperature and plot number	1982				1983				1984				1985			
	Control plot	Treated plot	Treated minus control	Difference	Control plot	Treated plot	Treated minus control	Difference	Control plot	Treated plot	Treated minus control	Difference	Control plot	Treated plot	Treated minus control	Difference
				Percent				*Percent*				*Percent*				*Percent*
Shelterwood:																
2, undisturbed	937.3	797.3	-140.0	-14.9	879.8	946.3	66.5	7.6	688.1	805.7	117.6	17.1	767.2	868.7	101.5	13.2
2, scarified									688.1	912.8	224.7	32.6	767.2	945.0	177.8	23.2
2, disturbed									688.1	861.7	173.6	25.2	767.2	926.1	158.9	20.7
6, undisturbed	853.3	905.7	52.4	6.1	795.9	820.6	24.7	3.1	683.2	860.3	177.1	25.9	710.5	967.4	256.9	36.2
6, scarified									683.2	884.8	201.6	29.5	710.5	978.6	268.1	37.7
6, disturbed									683.2	753.9	70.7	10.3	710.5	918.4	207.9	29.3
8	853.3	1177.4	324.1	38.0	795.9	1116.5	320.6	40.3	683.2	985.6	302.4	44.2	710.5	1051.4	340.9	48.0
Mean				9.7				17.0				26.4				29.8
Clearcut:																
7	853.3	908.6	55.3	6.5	795.9	937.3	141.4	17.8	683.2	826.7	143.5	11.9	710.5	915.6	205.1	28.9
13					1011.5	752.5	259.0	-25.6	733.6	816.2	82.6	11.3	660.1	853.3	193.2	29.3
Mean				6.5				-3.9				11.6				29.1
Clearcut and burned:																
1	937.3	935.9	-1.4	0	879.8	1106.7	226.9	25.8	688.1	1086.4	397.9	57.8	767.2	1111.6	344.4	44.9
11	882.7	760.2	-122.5	-13.9	1011.5	1030.4	18.9	1.9	733.6	1159.9	426.3	58.1	660.1	1247.4	587.3	89.0
14									733.6	946.4	212.8	29.0	660.1	940.8	280.7	42.5
Mean				-7.0				13.8				48.3			58.8	
Thinned, 4	876.4	796.6	-79.8	-9.1	853.3	761.6	-91.7	-10.7	693.0	587.3	-105.7	-15.2	657.3	736.4	79.1	12.0

[a] Values for logged plots are compared to those for the undisturbed controls.

Table 3—Soil degree-day values at the 20-cm depth for the 16-week growing season (last week in May to mid-September) in 1982 (before logging) and the first 3 years after logging (1983-85) by logging treatment, soil-temperature plot, and site preparation[a]

Logging treatment soil-temperature and plot number	1982				1983				1984				1985			
	Control plot	Treated plot	Treated minus control	Difference	Control plot	Treated plot	Treated minus control	Difference	Control plot	Treated plot	Treated minus control	Difference	Control plot	Treated plot	Treated minus control	Difference
				Percent				*Percent*				*Percent*				*Percent*
Shelterwood:																
2, undisturbed	637.0	491.4	-145.6	-22.9	632.8	626.3	-6.5	-1.0	457.1	611.1	154.0	33.7	572.6	746.2	173.6	30.3
2, scarified									457.1	717.5	260.4	57.0	572.6	858.2	285.6	49.9
2, disturbed									457.1	642.6	185.5	40.6	572.6	786.8	214.2	37.4
6, undisturbed	519.4	582.4	63.0	12.1	562.1	534.1	-28.0	-5.0	456.4	616.0	159.6	35.0	496.3	769.3	273.0	55.0
6, scarified									456.4	784.0	327.6	71.8	496.3	882.7	386.4	77.9
6, disturbed									456.4	585.2	128.8	28.2	496.3	815.5	319.2	64.3
8	519.4	823.2	303.8	58.5	562.1	936.6	374.5	66.6	456.4	859.6	403.2	88.3	496.3	958.3	462.0	93.1
Mean				15.9				20.2				50.7				58.3
Clearcut:																
7	519.4	548.1	28.7	5.5	562.1	723.8	161.7	28.8	456.4	660.1	203.7	44.6	496.3	804.3	308.0	62.1
13					404.6	427.7	23.1	5.7	266.7	473.9	207.2	77.7	284.2	522.2	238.0	83.7
Mean				5.5				17.2				61.2				72.9
Clearcut and burned:																
1	637.0	716.1	79.1	12.4	632.8	893.2	260.4	41.2	457.1	987.0	529.9	115.9	572.6	1068.2	495.6	86.6
11	436.8	287.0	-149.8	-34.3	404.6	555.8	151.2	37.4	266.7	938.0	671.3	251.7	284.2	1070.3	786.1	276.6
14									266.7	497.7	231.0	86.6	284.2	547.4	263.2	92.6
Mean				-11.0				39.3				151.4				151.9
Thinned, 4	631.2	493.2	-120.7	-19.7	592.3	531.3	-61.6	-10.4	499.8	373.8	-126.0	-25.2	493.5	590.8	97.3	19.7

[a] Values for logged plots are compared to those for undisturbed controls.

Measurements of soil temperature at a depth of 10 cm obtained in 1982 from undisturbed white spruce stands are in close agreement with measurements in similar stands on flood-plain sites. Viereck and others (1983) present values of 798 and 1140 (average 969) for soil degree-days measured at a depth of 10 cm in two mature white spruce stands on flood plains. Our comparable values for the 12 undisturbed plots on Willow Island ranged between 760 and 1177 with an average of 892.

The logging treatments were done during winter 1982-83. The soil-temperature measurements taken during summer 1983 indicated that tree removal and soil disturbance had apparently increased soil temperatures in some plots (figs. 2 and 3). The differences were, on the whole, rather small and inconsistent, and statistical analysis of values for soil degree-days at both the 10- and 20-cm depths showed differences between the control and treated plots to be nonsignificant (table 4). This result was somewhat surprising because we had expected that the logging treatments would be followed immediately by substantial increases in soil temperature. Indeed, these types of increases did occur at the 20-cm depth on the two clearcut and burned plots (table 3) but did not occur to the same extent on the other treated plots. We think the main reason for the slow temperature response was that the treatments were not completed until the end of the 1983 growing season: Burning on two of the clearcuts was not completed until the end of July, and scarification treatments on shelterwood units were not finished until fall 1983. Because these additional treatments would be expected to have considerable effect on soil temperatures, the delay in their implementation may explain the relatively small soil-temperature response during the first year.

Increases in soil temperature on treated plots were considerable during the second and third growing seasons (1984-85) after logging (tables 2 and 3 and figs. 2 and 3). In fact, in 1985 soil temperatures on the treated plots still seemed to be increasing relative to the control plots (fig. 3). Statistical analysis of soil degree-days at depths of 10 and 20 cm indicated that temperatures increased significantly ($P < 0.01$ at 10 cm and $P < 0.05$ at 20 cm) during both the 1984 and 1985 measurement periods (table 4). Temperature increases in 1985 at the 10-cm depth on logged plots vs. control plots averaged 20, 26, and 66 percent for shelterwood, clearcut, and clearcut and burned plots, respectively. The comparable figures for temperatures at 20 cm are considerably higher: 42, 70, and 163 percent for shelterwood, clearcut, and clearcut and burned plots, respectively (fig. 3).

Increases in soil temperature due to the logging treatments were actually greater at the 20-cm depth than they were at 10 cm. Temperature increases were also substantial at 50 cm, especially where shallow permafrost had existed before the logging treatments (fig 4). Heat conductivity is apparently efficient in these soils, which allows the rapid downward distribution of heat energy. The rapid conductivity may be partially the results of generally large amounts of soil moisture. Water, although it has a high specific heat, also has high thermal conductivity; thus moist soils conduct heat more efficiently than do dry soils. The effect of increased soil temperatures at depth on root development should be investigated. We can hypothesize that the volume of soil used effectively by plant roots substantially expands with increased soil temperatures such as we measured.

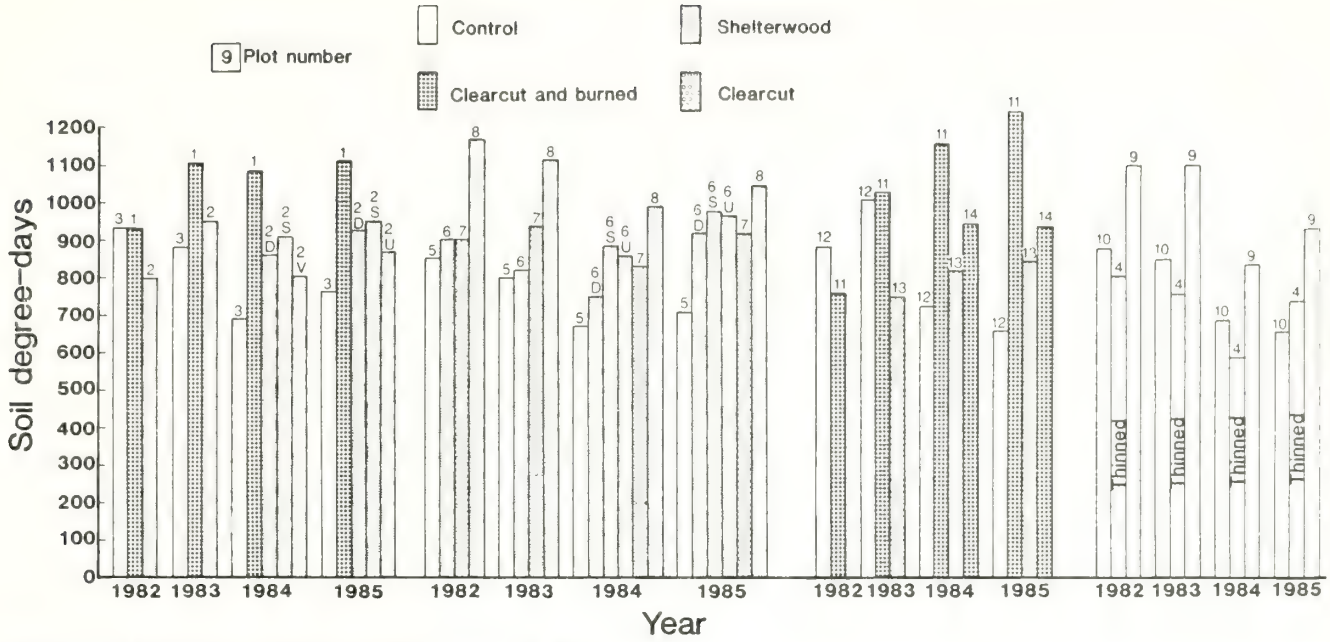


Figure 2—Soil degree-day values at a depth of 10 cm on the control, clearcut, shelterwood, and thinned plots before logging (1982) and the first 3 years after logging (1983-85).

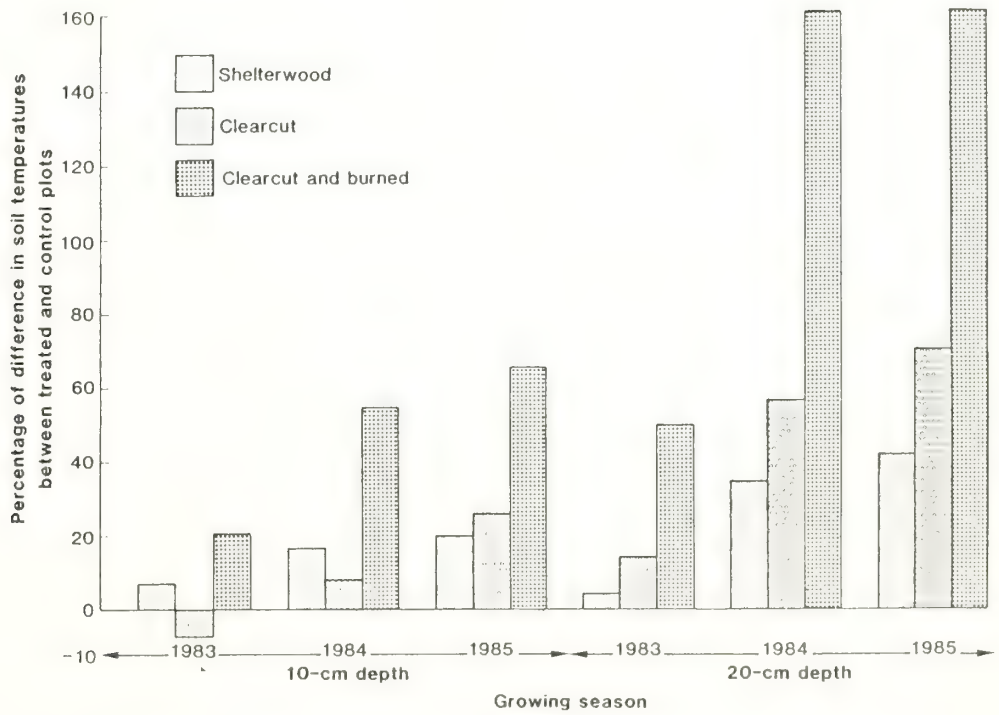


Figure 3—Differences in soil temperatures at depths of 10 and 20 cm from undisturbed controls at shelterwood, clearcut, and clearcut and burned locations.

Table 4—Means and standard errors of soil degree-day values at soil depths of 10 and 20 cm on the control and logged plots during summers in 1982 (before logging) and the first 3 years after logging (1983-85)[a]

Soil depth, treatment, and number of plots	Soil degree-days			
	1982	1983	1984	1985
At 10 cm:				
Control (n = 3)[b]	891.1 ± 24.6	895.6 ± 62.8a	701.6 ± 16.0a	712.6 ± 30.9a
Shelterwood (n=3)	960.1 ± 113.0	961.1 ± 85.7a	867.1 ± 66.9a	973.2 ± 40.9b
Clearcut (n=2)	908.6[c]	844.9 ± 92.4a	821.4 ± 5.2a	884.4 ± 31.1b
Clearcut and burned (n=3)	848.0 ± 87.8[d]	1,068.6 ± 38.1[d]a	1,064.2 ± 62.6b	1,099.9 ± 88.7c
At 20 cm:				
Control (n=3)	531.1 ± 58.1	533.2 ± 67.4a	393.4 ± 63.3a	451.0 ± 86.2a
Shelterwood (n=3)	632.3 ± 98.9	699.0 ± 121.4a	695.8 ± 83.5ab	859.3 ± 50.0b
Clearcut (n=2)	548.1[c]	575.8 ± 145.2a	567.0 ± 93.1ab	663.2 ± 141.1ab
Clearcut and burned (n=3)	501.6 ± 214.5[d]	724.5 ± 167.3[d]a	807.6 ± 155.6b	895.3 ± 173.9b

[a] Values followed by the same roman letter are not significantly different (P = 0.05).
[b] Temperature control plots 3, 5, and 12.
[c] Only 1 plot measured in 1982
[d] Only 2 plots measured in 1982 and 1983.

During late summer and fall 1983, blade scarification treatments were undertaken in the shelterwood areas. Areas 2-3 m in diameter were left where all organic materials were stripped off and bare mineral soil exposed. Intermixed with these scarified areas were areas where the forest floor had been disturbed and where the forest floor was undisturbed. Because we felt these conditions might be associated with different temperature regimes, soil temperatures were measured separately for each of the three shelterwood forest floor conditions in plots 2 and 6 during 1984 and 1985. As expected, soil temperature at 10- and 20-cm depths were consistently higher under scarified areas than they were under the other two conditions (tables 2 and 3). These differences were generally not large, and analysis of variance indicated they were not significantly different from values for the other shelterwood conditions. Perhaps the scarified areas were too small to exhibit the substantial temperature increases we expected.

The effect on soil temperature of slash burning plus clearcutting was dramatic: Increases in soil temperature were two to three times greater when clearcuts were slash burned than when they were not (tables 2 and 3, fig. 3). The average value for soil degree-days for 1985 at the 10-cm depth was 884 for clearcuttings and 1,199 for clearcuttings with burning. Comparable figures for the 20-cm depth were 663 for clearcuttings and 895 for clearcuttings with burning. The latter figure represents a sizable (2-1/2 times) increase over the soil degree-day value for the undisturbed control. Fires on both burned cutting units consumed logging slash almost completely and large portions of the forest floor. As a result, much of the organic insulating layer was removed, thus allowing the mineral soil to heat much more quickly. The blackened soil surface after the fires also undoubtedly contributed to increased soil temperatures because of more efficient absorption of the Sun's energy.

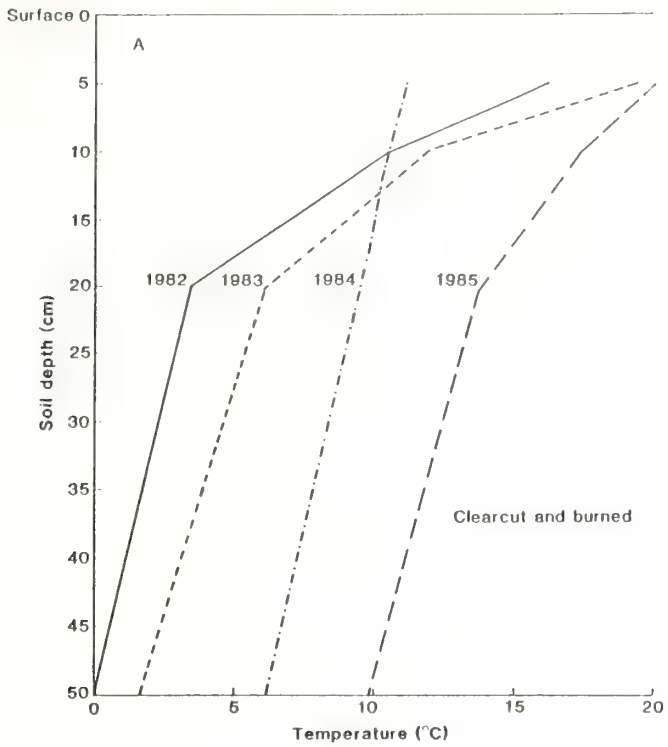


Figure 4—**A.** Soil temperature profile in mid-July at a clearcut and burned plot (11) before logging (1982) and the first 3 years after treatment (1983-85).

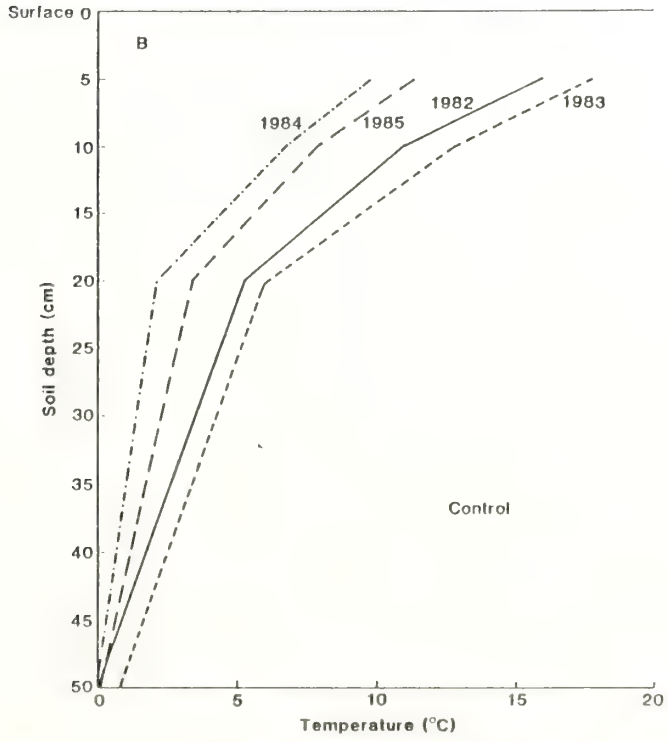


Figure 4—**B.** Soil temperature profile in mid-July on a paired, undisturbed control plot (12) for 1982-85.

The delayed response of soil temperature to the thinning treatment needs some explanation (tables 2 and 3). Actual thinning operations on the plot did not begin until winter 1983-84, when the trees to be removed were felled. The downed trees remained on the plot throughout the 1984 measurement period, and the slash provided additional insulation to the mineral soil. Because of this the soil temperatures for the treated plot for 1984 were slightly lower than those for the control plot. The felled trees were removed during winter 1984-85, so that only the final thinned stand remained on the plot during the 1985 growing season. Removing a substantial portion of the tree canopy apparently allowed more of the Sun's energy to reach the soil surface, as soil temperature warmed appreciably during 1985 (tables 2 and 3).

Year-to-year variations in soil temperatures were considerable. Although all four summers had cool, rainy periods, data from the control plots indicated that the summers of 1982 and 1983 produced noticeably warmer soil temperatures (tables 2 and 3, fig. 5). On most control plots, soil temperatures were coolest in 1984 and warmed somewhat in 1985.

Strong yearly variation was also evident in frost distribution within the measured soils (table 5). The data collected for frost during the four growing seasons strongly reinforced the view that many soils on Willow Island are on the margin of developing permafrost; these soils may have deep frost throughout the growing season if summer temperatures are cool, but not during the following summer if temperatures are higher. This is why many soils we sampled showed continuous frost in only two of the four sampling periods. The only plots to show consistent, fairly shallow permafrost were control plots 5 and 12. With gradually increasing forest floor thickness, and in the absence of logging, fire, or other radical disturbance, a progressive increase in the area of Willow Island underlain by soils containing permafrost is expected.

Probably the most spectacular change in soil-temperature regime occurred on plot 11 (clearcut and burned). Before treatment (1982), this site had a shallow permafrost table and soil temperatures that were actually substantially cooler than the nearby control (tables 2, 3, and 4). By the second summer after treatment (1984), all frost had left the profile and the soil degree-day value for the 20-cm depth was up to an astounding 938 vs. only 267 for the control. At the 10-cm depth, the soil degree-day value went from 760 (1982) to 1247 (1985). An increase in soil temperature of this magnitude indicates a substantial increase in potential site productivity. A soil degree-day value of 760 is typical of black spruce sites, and a value of 1247 is higher than the average values reported for the most highly productive balsam poplar and white spruce sites (Viereck and others 1983).

Effects of Logging Treatment on the Natural Vegetation

The initial responses of the vegetation to the five silvicultural treatments differed considerably among treatments, in part because of differences in the original vegetation types. What follows is a discussion of how logging treatment affected the survival of the prelogged vegetation and the development of the natural vegetation for the first 2-3 years after logging. Tables 6, 7, and 8 present information on pretreatment and control vegetation and the response to the silvicultural treatments for each community type. We will summarize the effects by silvicultural treatment regardless of original forest type.

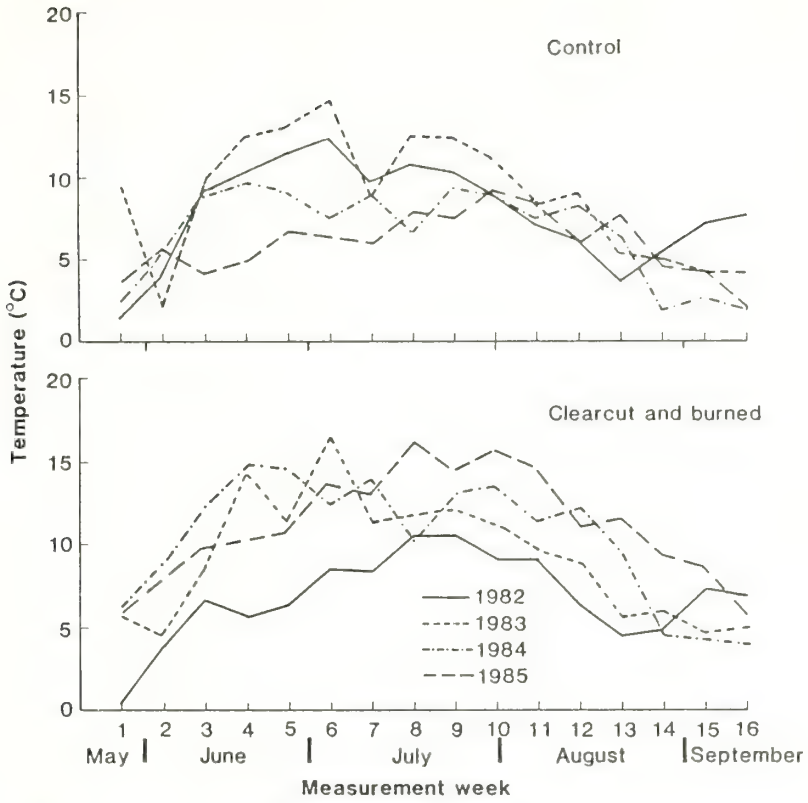


Figure 5—Summer soil temperatures at a depth of 10 cm on an undisturbed control plot (12) and a nearby clearcut and burned plot (11) for 1982-85.

Table 5—Maximum depth to frost at the end of the growing season (mid-September) in 1982 (before logging) and in the first 3 years after logging (1983-85) after logging on each of the soil-temperature plots[a]

Soil-temperature plot number	Treatment	Depth to frost			
		1982	1983	1984	1985
		Centimeters			
3	Control	No frost	168	128	No frost
1	Clearcut and burned	No frost	No frost	No frost	No frost
2	Shelterwood	No frost	No frost	No frost	No frost
5	Control	61	65	60	67
6	Shelterwood	No frost	68	147	No frost
7	Clearcut	No frost	186	No frost	No frost
8	Shelterwood	158	106	No frost	No frost
12	Control	69	83	74	82
11	Clearcut and burned	66	87	No frost	No frost
13	Clearcut		87	99	No frost
14	Clearcut and burned			87	112
9	Control	No frost	No frost	No frost	No frost
10	Control	No frost	No frost	No frost	No frost
4	Thinned	No frost	No frost	128	No frost

[a] Each value is based on 8 separate measurements of frost depth.

Table 6—Average percentage of cover and average percentage of frequency of the vegetation before and after 3 silvicultural treatments in the open *Picea glauca/Alnus crispa-A. tenuifolia/Vaccinium vitis-idaea/Hylocomium splendens* forest type, Willow Island

Plant species and category by layer	Control		Treatment											
	Pretreatment, units 2-9		Postclearcut, units 3, 6, 9				Postshelterwood 14-m spacing, units 2, 7				Postshelterwood 9-m spacing, units 4, 5, 8			
			Year 1		Year 2		Year 1		Year 2		Year 1		Year 2	
	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency
	Percent													
Tree, sapling, and seedling canopy:	21.5	100	0.2	24	0.7	55	2.7	90	3.6	95	4.8	80	4.6	93
Betula papyrifera		83								38				33
Picea glauca		100						90		90		80		93
Picea mariana		1												
Populus balsamifera		7								50				27
Tree, sapling and seedling stem cover	1.4	58	.2	24	.6	55	1.9	85	1.7	95	.4	23	.8	72
Tree seedling canopy (only):	.6	38	.2	24	.7	55	1.1	90	2.3	95	.3	20	1.0	78
Betula papyrifera	.1	7	.1	7	.2	20	.3	23	.4	35	.1	5	.1	12
Picea glauca	.5	29	.2	20	.4	40	.8	78	.9	80	.2	15	.7	58
Populus balsamifera	[a]+	2			.2	8	.2	13	1.1	23	.1	5	.2	10
Populus tremuloides					.2	15			.1	5			+	2
Tall shrub canopy:	62.5	100	6.3	100	32.4	97	11.0	100	22.5	100	17.7	100	39.0	100
Alnus crispa	35.1	63	1.1	24	.9	19			1.6	15	2.2	13	5.0	28
Alnus tenuifolia	20.5	44	.3	14	1.3	15	5.0	70	6.2	58	6.6	52	7.5	47
Betula glandulosa					+	2								
Rosa acicularis	13.8	98	4.7	98	27.6	96	7.3	98	16.5	100	10.2	100	26.9	100
Rubus idaeus			.1	5	.1	6	.1	3	.1	3			.1	7
Salix alaxensis									.1	3				
Salix arbusculoides	.1	4	.1	8	.3	13	.1	3						
Salix bebbiana/glauca	+	3	+	2	.1	7	.2	15	.2	13				
Salix novae-angliae	.2	1	.3	6	.5	5			.1	3			.2	2
Salix species	+	1	+	4			.1	10	.1	8				
Viburnum edule	1.5	54	.4	35	.4	29	.6	55	.8	43	.4	32	.6	48

See footnote at end of table.

Table 6—Average percentage of cover and average percentage of frequency of the vegetation before and after 3 silvicultural treatments in the open *Picea glauca/Alnus crispa-A. tenuifolia/Vaccinium vitis-idaea/Hylocomium splendens* forest type, Willow Island (continued)

Plant species and category by layer	Control		Treatment											
	Pretreatment, units 2-9		Postclearcut, units 3, 6, 9				Postshelterwood 14-m spacing, units 2, 7				Postshelterwood 9-m spacing, units 4, 5, 8			
			Year 1		Year 2		Year 1		Year 2		Year 1		Year 2	
	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency
	Percent													
Low shrub canopy:	35.7	98	2.4	82	7.8	83	5.4	90	10.5	90	8.9	97	21.5	98
Empetrum nigrum	+	1					+	3	.1	3				
Ledum groenlandicum	.2	3	+	3	+	3	+	3			.1	3	.1	3
Linnaea borealis	13.4	92	.8	56	4.5	66	2.8	65	7.3	68	3.2	82	11.4	90
Potentilla fruticosa							+	3						
Ribes triste	.1	8	+	4	.1	13	.1	5	.1	8	.1	5	.2	15
Salix myrtillifolia	.2	1	+	2	.1	3					.2	2	.1	2
Vaccinium uliginosum	.3	6	+	2	.1	7	.2	5	+	3	.2	10	.5	13
Vaccinium vitis-idaea	24.9	86	1.9	60	3.6	68	2.9	60	3.2	53	6.7	92	11.4	93
Herb canopy:	42.6	100	9.9	98	43.3	97	14.1	100	49.8	100	9.8	98	37.3	98
Arctagrostis latifolia			+	2	1.3	20			3.5	20			.2	5
Astragalus alpinus			1.5	2	.7	3					.1	2	.1	2
Boschniakia rossica	+	1												
Calamagrostis canadensis	2.2	26	1.1	20	6.2	20	2.4	38	6.3	35	1.0	27	9.3	33
Carex disperma	0.2	3			.1	3								
Carex species	1.5	19	.2	14	.7	23	.1	8	.4	15	.1	5	1.9	25
Carex vaginata	.8	7					.1	8	.2	10	2.1	32	1.2	17
Cornus canadensis	10.2	81	3.4	75	12.3	80	3.6	83	8.9	85	3.6	70	9.1	72
Epilobium adenocaulon/hornemanni			+	2	.2	7							+	2
Epilobium angustifolium	+	1	+	2	.6	23	.2	15	1.6	28	.2	2	.6	12
Equisetum arvense	18.7	84	3.3	70	18.9	85	6.0	88	23.7	95	1.7	58	11.4	80
Equisetum scirpoides	9.0	53	.2	14	1.3	38	2.8	73	6.7	75	.7	28	2.6	42
Galium trifidum			+	2			.1	3	.3	8	+	2	.1	2
Geocaulon lividum	3.4	53	.3	27	.1	9	.1	13	.1	8	1.2	40	.9	30
Goodyera repens	.4	21												
Hedysarum alpinum	1.0	9	.7	11	1.9	10	.1	5	.7	8	.4	15	1.1	18
Iris setosa							.1	5	.2	5				
Lycopodium annotinum	.1	4	+	2	.1	3							.9	10

Table 6—Average percentage of cover and average percentage of frequency of the vegetation before and after 3 silvicultural treatments in the open *Picea glauca/Alnus crispa-A. tenuifolia/Vaccinium vitis-idaea/Hylocomium splendens* forest type, Willow Island (continued)

Plant species and category by layer	Control		Treatment											
	Pretreatment, units 2-9		Postclearcut, units 3, 6, 9				Postshelterwood 14-m spacing, units 2, 7				Postshelterwood 9-m spacing, units 4, 5, 8			
			Year 1		Year 2		Year 1		Year 2		Year 1		Year 2	
	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency
	Percent													
Mertensia paniculata	.4	11	.2	19	1.6	27	.4	8	3.2	8	.1	10		
Moehringia lateriflora	+	4	+	2	+	2			+	3				
Moneses uniflora	.5	21									+	2	+	2
Platanthera obtusata	+	2											+	2
Poa species					4.7	18			.2	5	.2	8	2.2	18
Potentilla palustris							+	3	.3	3				
Pyrola asarifolia/chlorantha	4.6	45	.1	6	.2	7	.2	13	.5	13	1.0	47	2.2	53
Pyrola minor													.1	5
Pyrola secunda	1.2	36	.1	6	.1	13	.2	15	.4	20	.1	5	.4	25
Pyrola species					+	4			.1	13				
Rorippa islandica							.1	5	.3	5				
Rubus arcticus	.2	4	.1	7	.5	5	.2	8	.1	5				
Saussurea angustifolia	+	1	.1	3	.1	3					+	2	+	2
Stellaria longipes					.1	5	+	3	.2	13			+	3
Taraxacum species					+	2								
Trientalis europaea							+	3						
Unidentified Compositae									.1	5				
Unidentified Cruciferae									.1	3				
Unidentified Graminae	.7	9	.6	15			.1	3						
Unidentified herb									+	3				
Moss canopy:	65.6	99	.3	30	5.1	77	1.6	63	9.6	95	3.7	65	11.3	83
Aulacomnium palustre					.2	6			.2	5				
Brachythecium salebrosum									.6	18			+	2
Bryum species	.6	14			.8	17	.2	8	.2	18			.6	17
Ceratodon purpureus	.1	1												
Climacium dendroides													+	2
Dicranum species	1.1	32			.4	16			1.2	35	.1	7	.1	5
Distichum capillaceum					+	2								

Table 6—Average percentage of cover and average percentage of frequency of the vegetation before and after 3 silvicultural treatments in the open *Picea glauca/Alnus crispa-A. tenuifolia/Vaccinium vitis-idaea/Hylocomium splendens* forest type, Willow Island (continued)

Plant species and category by layer	Control		Treatment											
	Pretreatment, units 2-9		Postclearcut, units 3, 6, 9				Postshelterwood 14-m spacing, units 2, 7				Postshelterwood 9-m spacing, units 4, 5, 8			
			Year 1		Year 2		Year 1		Year 2		Year 1		Year 2	
	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency
	Percent													
Drepanocladus species	3.0	49			+	3	.1	5			.1	3	.2	15
Eurhynchium species	7.2	69			.7	26	.2	10	1.2	40	.4	17	.4	20
Homalothecium nitens	.2	3												
Hylocomium splendens	48.3	91	.2	19	.7	30	.3	20	4.1	45	2.9	65	9.9	78
Marchantia polymorpha					.4	11							+	2
Mnium species	.2	8												
Pleurozium schreberi	1.2	12	+	3	.4	3	+	3	.6	8	+	3	.1	2
Polytrichum species					.1	5								
Ptilidium ciliare							.1	3			+	2	.1	2
Ptilium crista-castrensis	.7	6					+	3	+	3	+	2	.1	3
Rhytidiadelphus triquetrus	5.6	22	+	4			.8	25	1.8	15	+	3	+	3
Rhytidium rugosum			.1	8							.5	2	.3	3
Unidentified leafy liverwort	1.9	29												
Unidentified moss	.7	9	.1	7	2.0	26	.4	23					.1	7
Lichen:	.5	19			+	2			+	3			.1	5
Cladonia gracilis	+	1											+	2
Cladonia species	.1	4			+	2			+	3			+	3
Peltigera aphthosa	.1	8												
Peltigera canina	.3	13												

[a] + means the value is less than 0.1 percent.

Table 7—Average percentage of cover and average percentage of frequency of the vegetation before and after 3 silvicultural treatments in the open *Picea glauca/Alnus tenuifolia/Hylocomium splendens* forest type, Willow Island

Plant species and category by layer	Control		Treatment											
	Pretreatment, units 11-15		Clearcut/burn, unit 12				Clearcut, units 13, 15				Shelterwood, 9-m spacing, units 11, 14			
			Year 1[a]		Year 2		Year 1		Year 2		Year 1		Year 2	
	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency
	Percent													
Tree, sapling and seedling canopy:	18.8	100	.7	55	.7	55	.3	48	.9	48	8.7	100	6.4	100
Betula papyrifera		29						48		48				
Picea glauca		100						40		40		100		100
Populus balsamifera		84								40				90
Tree, sapling and seedling stem cover	.7	33	.7	55	.6	55	.2	20	.3	28	.6	20	1.2	55
Tree seedling canopy only:	.4	23	.7	55	.7	55	.2	20	.3	28	.2	13	.7	58
Betula papyrifera							.1	3						
Picea glauca	.2	13	.4	40	.1	5	.2	13	.3	20	.2	10	.6	55
Picea species	.1	7			.2	15								
Populus balsamifera	[b]+	3	.1	5			.1	5	.1	8	.1	3	.2	3
Populus tremuloides			.4	40	.7	55								
Tall shrub canopy:	39.2	100	3.0	75	4.8	80	6.4	90	31.3	90	4.8	93	18.6	95
Alnus tenuifolia	28.3	73					1.6	40	5.0	40	1.6	43	4.8	50
Rosa acicularis	13.1	89	2.7	70	4.6	75	5.3	85	24.0	90	3.4	85	14.6	93
Rubus idaeus			.1	5	.1	5			.1	3			.1	3
Salix arbusculoides					.1	10								
Salix bebbiana/glauca					.3	25								
Salix novae-angliae											.1	3	.1	3
Salix species			.1	5	.2	20								
Viburnum edule	1.7	48	.2	20	.2	20	.4	25	2.6	28	.4	38	1.1	55
Low shrub canopy:	26.9	70	.1	5	.1	5	2.2	50	5.3	53	1.5	58	7.6	60
Arctostaphylos rubra	.9	4					.3	5	.1	5	+	3	.1	3
Linnaea borealis	23.3	68					1.9	43	5.0	43	1.5	58	7.4	60
Potentilla fruticosa											+	3	.1	3
Vaccinium vitis-idaea	4.4	9	.1	5	.1	5	.1	10	.2	10				

See footnote at end of table.

Table 7—Average percentage of cover and average percentage of frequency of the vegetation before and after 3 silvicultural treatments in the open *Picea glauca/Alnus tenuifolia/Hylocomium splendens* forest type, Willow Island (continued)

Plant species and category by layer	Control		Treatment											
	Pretreatment, units 11-15		Clearcut/burn, unit 12				Clearcut, units 13, 15				Shelterwood, 9-m spacing, units 11, 14			
			Year 1[a]		Year 2		Year 1		Year 2		Year 1		Year 2	
	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency
	Percent													
Herb canopy:	31.0	97	.6	20	3.4	50	5.6	90	21.9	90	6.2	90	18.3	93
Calamagrostis canadensis	.3	4					.2	10	1.8	13	.4	8	2.3	13
Capsella bursa-pastoris					.5	5								
Carex species	2.3	25	.1	5	.3	25	1.4	38	2.0	35	.3	10	.4	10
Carex vaginata											2.2	10	2.2	13
Cornus canadensis	.7	9					.6	15	.8	10	.3	15	.8	15
Elymus alaskanus	.1	2												
Epilobium angustifolium	.2	7	.5	10	2.3	30	.2	10	1.2	13	.1	3	1.6	13
Equisetum arvense	11.4	60			.4	5	1.6	50	7.9	70	2.2	43	7.3	63
Geocaulon lividum	10.8	74					.6	40	.2	15	.7	40	1.3	30
Goodyera repens	.4	14												
Hedysarum alpinum	2.1	22	.1	5	.1	5	1.1	33	2.3	28	.2	8	.8	10
Moehringia lateriflora	.5	10					.4	23	4.9	43	+	3	1.0	15
Moneses uniflora	.7	32					.1	8			.1	8		
Platanthera obtusata	.1	6									+	3	.1	3
Poa species							.1	5	.7	10	+	3	.2	3
Pyrola asarifolia/chlorantha	2.7	27					.1	10	.6	28	.1	8	.7	23
Pyrola secunda	2.7	58					+	3	.3	23	.4	30	.6	33
Pyrola species							.1	10			.3	18		
Rubus arcticus	.9	7					.3	8	1.5	10	.3	8	1.2	10
Stellaria longipes							.1	5	.3	5				
Trientalis europaea	.1	2					+	3	.1	3	+	3	.1	3
Unidentified Graminae	.1	4					.1	8	.5	8			.1	3
Moss canopy:	78.9	99	1.0	45	17.7	100	.5	40	1.7	80	5.0	85	33.9	95
Bryum species	.2	10							.1	10	+	3	.2	13
Ceratodon purpureus			.8	35	17.1	100								
Dicranum species	.8	34							.1	5	.1	8	.3	18
Drepanocladus species	2.9	53							+	3	+	3		

Table 7—Average percentage of cover and average percentage of frequency of the vegetation before and after 3 silvicultural treatments in the open *Picea glauca/Alnus tenuifolia/Hylocomium splendens* forest type, Willow Island (continued)

Plant species and category by layer	Control		Treatment											
	Pretreatment, units 11-15		Clearcut/burn, unit 12				Clearcut, units 13, 15				Shelterwood, 9-m spacing, units 11, 14			
			Year 1[a]		Year 2		Year 1		Year 2		Year 1		Year 2	
	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency
	Percent													
Eurhynchium species	5.5	68							.1	13	.5	10	.3	13
Hylocomium splendens	72.5	98					.5	40	1.3	68	4.2	83	33.3	90
Marchantia polymorpha			.3	10	1.0	45							.1	5
Mnium species	.1	10			.1	5								
Pleurozium schreberi	.3	6									.2	8		
Polytrichum species	.5	3					+	3			.3	5	.1	8
Ptilidium ciliare	.3	4									.1	5		
Ptilium crista-castrensis	.1	4												
Rhytidium rugosum	.1	4												
Unidentified leafy liverwort	.3	16												
Unidentified moss	.3	5	.1	10					.2	5	+	3	+	3
Lichen:	1.5	38					.1	10	.1	10	.1	10	.1	8
Cladonia gonecha									+	3				
Cladonia gracilis	+	4					+	3						
Cladonia species	.1	3					+	3					+	3
Peltigera aphthosa	.7	18					.1	10	.1	5	.1	5	.1	5
Peltigera canina	.7	27							+	3	.1	5		
Peltigera species									+	3				

[a] Treatment not complete until August 1983 so the first post growing season is 1984 or 1 year later than for the other treatments.

[b] + means the value is less than 0.1 percent.

Table 8—Average percentage of cover and percentage of frequency of the vegetation before and after 1 silvicultural treatment in the Woodland *Picea glauca/Ledum groenlandicum-Vaccinium vitis-idaea/ Hylocomium splendens* forest type, Willow Island

Plant species and category by layer	Control; pretreatment, unit 16		Treatment; postclearcut/burn, unit 16					
			Year 0		Year 1		Year 2	
	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency
	Percent							
Tree, sapling and seedling canopy:	18.8	100	0	0	.8	75	1.0	95
Betula papyrifera		100						
Picea glauca		100						
Picea mariana		75						
Tree, sapling and seed stem cover	1.8	75			.8	75	1.0	95
Tree seedling canopy only:	2.0	30	0	0	.8	75	1.0	95
Betula papyrifera	.3	20					.6	55
Picea glauca	.2	10					.1	10
Picea mariana	1.8	20						
Populus balsamifera							.6	55
Populus tremuloides					.8	75	.9	90
Tall shrub canopy:	16.9	100	0	0	.1	10	.9	80
Alnus crispa	.5	5						
Rosa acicularis	11.4	95			.1	5	.1	10
Salix arbusculoides	.1	5			.1	5	.2	15
Salix bebbiana/glauca	6.8	55					.6	60
Salix novae-angliae							.6	65
Low shrub canopy:	80.1	100	0	0	0	0	0	0
Empetrum nigrum	9.5	20						
Ledum groenlandicum	31.8	65						
Linnaea borealis	5.3	60						
Vaccinium vitis-idaea	59.5	100						
Herb canopy:	31.3	100	0	0	54.0	100	71.6	100
Calamagrostis canadensis	2.5	75			.4	15	.9	15
Cornus canadensis	5.7	90						
Epilobium adenocaulon/hornemannii							.1	5
Epilobium angustifolium					1.4	60	1.2	75
Equisetum arvense	17.8	100			53.5	100	71.2	100
Equisetum scirpoides	.8	25						
Geocaulon lividum	8.4	95						
Lycopodium annotinum	.1	5						
Pyrola asarifolia/chlorantha	.2	20						
Pyrola secunda	.1	5						
Senecio species	.3	5						
Stellaria species	.1	5						
Taraxacum species							.1	5
Moss canopy:	65.4	100	0	0	26.4	100	56.6	100
Aulacomnium palustre	3.3	40						

Table 9--Average percentage of cover and average percentage of frequency of litter, logging debris, and other forest floor categories before and after silvicultural treatment, Willow Island[a]

Forest floor category by group	Control		Treatment													
	Pretreatment, units 2-9 and 11-16		Clearcut/burn, unit 12, 16				Clearcut, units 3, 6, 9, 13, 15				Shelterwood 14-m spacing, units 2, 7				Shelterwood 9-m spacing, units 4, 5, 8, 11, 14			
			Year 0		Year 1		Year 2		Year 1		Year 2		Year 1		Year 2		Year 1		Year 2	
	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency	Cover	Frequency
	Percent																			
Dead moss (initial posttreatment)									17.5	91			16.9	90			31.0	99		
Dead moss (end of season)									13.6	83			15.8	90			25.8	89		
Litter (initial posttreatment)			0.3	5					13.3	62			19.9	70			32.8	91		
Litter (end of season)	54.0	100	.4	10	0.1	3	20.0	100	66.8	100	49.1	97	71.4	100	43.0	100	62.2	99	29.6	98
Charred material (initial posttreatment):			99.0	100																
Ash cover			70.8	100																
Moderate burn severity			25.2	98																
Low burn severity			2.3	63																
Scorched			.2	10																
Charred material (end of season)			99.0	100	10.8	43	26.3	100			1.7	3								
Dead wood (initial posttreatment)			3.6	43																
Compressed logging debris (posttreatment):									67.8	100			57.2	98			51.0	99		
Litter and small diameter									48.2	100			45.7	98			42.9	99		
Medium diameter									11.6	61			8.4	40			5.4	39		
Large diameter									8.0	42			2.9	18			.2	20		
Loose debris (initial posttreatment)									38.7	100			43.7	100			42.5	100		
Dense debris (initial posttreatment)			2.3	28					7.2	80			11.0	90			7.6	72		
Dead snags (initial posttreatment)			1.9	73					1.4	30			1.1	23			.7	21		
Dead wood (end of season)	17.8	100	5.7	95	14.0	100	16.0	100	64.4	100	77.0	100	89.5	100	72.3	100	53.9	99	75.7	100
Mineral soil (initial posttreatment)			8.0	90					2.8	38			.9	30			.8	35		
Mineral soil (end of season)			8.0	90	35.4	93	15.3	98	.6	10	4.0	18	.2	10	.1	5	.1	1		
Organic soil (initial posttreatment)			.1	3					2.8	39			.3	18			.8	33		
Organic soil (end of season)					38.7	100	25.3	90	2.5	19	15.5	85	1.0	10	1.3	78	.2	7	2.3	51
Standing water									.1	1										

[a] Data is combined for all three forest types in which silvicultural treatments were made.

Figure 6—**A.** Open white spruce/thinleaf alder/feathermoss type (unit 12) before logging.

Figure 6—**B.** The same unit in June 1984 showing the results of clearcutting followed by burning in July 1983.

Figure 6—**C.** The same stand in 1985, 2 years after the silvicultural treatment, showing the slow recovery of the vegetation.

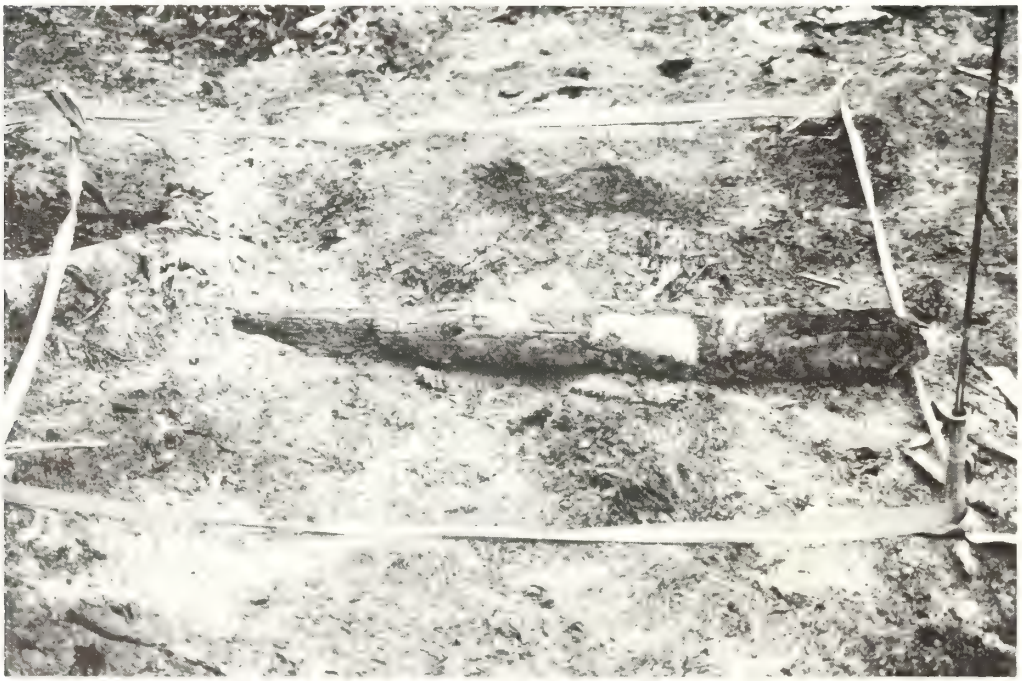


Figure 6—**D.** A 1-m^2 plot in unit 12 in 1984 showing charred logs and forest floor.

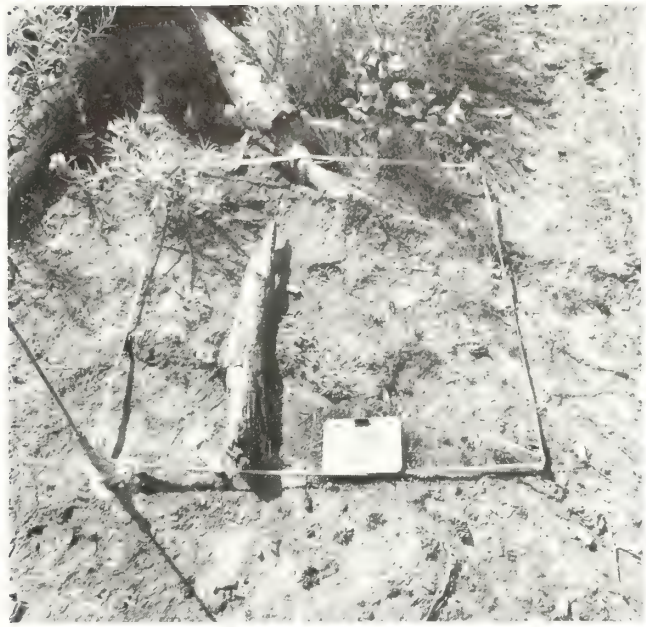


Figure 6—**E.** The same 1-m2 plot (but from a different angle) in 1985 showing condition of the forest floor and development of the vegetation.

Two years after the logging and burning, it appears that the sites may eventually be dominated by a mixed hardwood stand of upland and flood-plain species. Of special significance is the invasion of the burned sites by large numbers of aspen seedlings. Although aspen seedlings are occasionally found on newly established silt bars in the Tanana River, aspen seldom, if ever, persist to maturity. The first 3 years after logging were poor years for spruce seed on Willow Island, and thus the result has been low numbers of spruce seedlings in the burned clearcut units. Spruce seedlings occur but are outnumbered by *Populus tremuloides, P. balsamifera,* and *Betula papyrifera,* which are faster growing species. Neither *Alnus* species shows signs of vegetative recovery, and no *Alnus* seedlings have been found. The low shrubs, *Vaccinium vitis-idaea, Ledum groenlandicum,* and the feathermosses, *Hylocomium splendens* and *Pleurozium schreberi*, have been replaced by *Salix* spp., *Rosa acicularis, Calamagrostis canadensis, Equisetum arvense,* and the invading *Ceratadon purpureus* and *Marchantia polymorpha.*

Clearcut sites (unburned)--Clearcutting caused more disturbance of the vegetation and forest floor than did either of the shelterwood treatments but less disturbance than clearcutting with slash burning. Logging debris, consisting primarily of large- and small-diameter logs, branches, and needles, covered about 75 percent of the surface in the spring after the harvest. Much of the debris was compacted to several centimeters in depth, creating a poor seedbed for invading species; this may have accounted for the slow temperature response described in the section on soil temperature. Some mineral soil was exposed, especially at the landings and along skid trails, but the total was usually less than 10 percent (table 9 and fig. 7). Unlike the burned units, the unburned clearcuttings contained the live underground roots and rhizomes of many species, which allowed the plants to recover rapidly after the disturbance. Abundant basal sprouting from root crowns and undamaged lower stems also occurred. Although the feathermosses were not totally destroyed by the logging, the exposure to sunlight and drying during the summer after the logging effectively eliminated them from the units.

Figure 7—**A.** Open white spruce/thinleaf alder/feathermoss type (unit 13) before clearcutting.

Figure 7—**B.** The same location in June 1983, the first summer after clearcutting.

Figure 7—**C.** The same unit in 1985 showing a shrub canopy of *Alnus tenuifolia* and *Rosa acicularis*.

Figure 7—**D.** Typical logging debris in the same stand in June 1983, the first summer after clearcutting.

Of the 50 vascular species recorded in the plots before logging, only four—*Boschniakia rossica* (Cham. & Schlect.) Fedtsch., *Goodyera repens, Moneses uniflora,* and *Platanthera obtusata* (Pursh) Lindl.—were absent after the logging. In 1984, cover of *Arctostaphylos rubra* (Rehd. & Wilson) Fern., *Geocaulon lividum,* and *Viburnum edule* was still decreasing. Total live moss cover was drastically reduced, but of the 20 species recorded in the plots before logging, only 5—*Mnium* sp., *Polytrichum* sp., *Ptilium crista-castrensis* (Hedw.) De Not., *Rhytidiadelphis triquetrus,* and *Rhytidium rugosum* (Hedw.) Kindb.—were eliminated from all sites. Mosses eliminated from some but not all sites were *Dicranum* sp., *Drepanocladus* sp., and *Tomenthypnum nitens* (Hedw.) Loeske. The lichens were also eliminated or greatly reduced in all clearcut units (table 7).

Some species not recorded in the pretreatment plots were found in the plots after logging; these included *Rubus idaeus, Populus balsamifera, Epilobium adenocaulon* Hausk., *E. angustifolium, Stellaria longipes, Taraxacum* sp., and the nonvascular species, *Marchantia polymorpha* and *Aulacomnium palustre* (Hedw.) Schwaegr. Most of these species are the same as those invading the clearcut and burned sites.

Most of the surviving species developed rapidly once the canopy was removed. *Rosa acicularis* and *Calamagrostis canadensis* increased greatly in cover on all clearcut sites; and *Cornus canadensis, Equisetum arvense, Hedysarum alpinum, Mertensia paniculata,* and *Moehringia lateriflora* (L.) Frenzl increased in cover on some clearcut sites. After an initial decrease in 1983, the remaining species showed an increase in 1984.

Although cover values of most species had not reached pretreatment levels 2 years after logging, most were increasing rapidly and some, such as *Rosa acicularis* and *Calamagrostis canadensis*, had reached frequency and cover levels equal to or higher than those recorded before logging. In 1984, the leading dominants were *Rosa acicularis* (18-30 percent) for tall shrubs, *Linnaea borealis* (2-7 percent) for low shrubs, *Equisetum arvense* (4-35 percent) for herbs, and *Hylocomium splendens* (1-2 percent) for mosses. *Alnus tenuifolia, Vaccinium vitis-idaea, Calamagrostis canadensis, Cornus canadensis, Poa* sp., *Hedysarum alpinum,* and *Mertensia paniculata* attained cover values of at least 4 percent on some sites, however.

Most species characteristic of the pretreatment sites were present two years after clearcutting. Spruce seedlings were outnumbered by *Populus balsamifera* and *Betula papyrifera,* however. *Rosa acicularis* replaced *Alnus tenuifolia* and *A. crispa* as the dominant tall shrub. *Linnaea borealis* was more important in the low shrub layer than was *Vaccinium vitis-idaea. Hylocomium splendens,* with an original cover of 15-56 percent, survived in the logged stand, but the cover was reduced to an average of 2 percent.

Shelterwood; 14-m residual tree spacing--Disturbance of the vegetation and forest floor was less in the most open shelterwood treatments than in the clearcuts. The quantity and cover of logging debris was less, and pockets of relatively undisturbed vegetation surrounded some of the residual trees (table 9 and fig. 8). Mineral soil was only occasionally exposed, and only 1-2 percent cover of mineral soil was recorded in the plots in early summer 1983. More of the aboveground stems of the tall shrubs, especially alder, remained intact in the shelterwood plots than in the clearcut treatments. The cover of surviving tall shrubs was 9-13 percent in the 14-m residual tree spacing shelterwood compared to 6 percent in the clearcuttings. The shade created by the residual trees seems to have resulted in better survival of the original vegetation, especially the feathermosses, which had recovered in some areas to 11 percent cover by 1984.

Figure 8—**A.** Open white spruce/mixed alder/lingonberry/feathermoss type (unit 7) before logging.

Figure 8—**B.** The same location in June 1983, the first summer after a shelterwood treatment at a 14-m spacing.

Figure 8—**C.** Typical logging debris in June 1983, the first summer after the shelterwood treatment.

Species not reestablished after 2 years were *Ledum groenlandicum, Geocaulon lividum, Goodyera repens, Moneses uniflora,* and several mosses and lichens. Species invading some of the sites after logging included *Rubus idaeus, Epilobium angustifolium, Galium trifidum* L., *Iris setosa, Potentilla palustris* (L.) Scop., *Rorippa islandica* (Oeder) Barb., *Stellaria longipes,* and *Arctagrostis latifolia* (R.Br.) Griseb. Two years after logging, the dominant tall shrub species was *Rosa acicularis* (15-18 percent cover) although *Alnus tenuifolia* and to a lesser extent *A. crispa* were present and increasing in cover. *Linnaea borealis* and *Vaccinium vitis-idaea* dominated the low shrub layer, and *L. borealis* regained its pretreatment cover levels. The cover of *V. vitis-idaea* decreased initially but remained constant between 1983 and 1984 (tables 6 and 7).

In 1984, the dominant herbs in one or more of the units were *Cornus canadensis, Equisetum arvense, Calamagrostis canadensis, Arctagrostis latifolia, Mertensia paniculata,* and *Equisetum scirpoides* with total herb cover of up to 51 percent in some units. *Hylocomium splendens* was the dominant moss but occurred at only 3-5 percent cover, much lower than its pretreatment values (15-56 percent).

Although natural seedlings of *Picea glauca* were present, they were outnumbered and overtopped by *Populus balsamifera* seedlings.

Shelterwood; 9-m residual tree spacing--This denser shelterwood treatment resulted in the least disturbance of all the treatments in both open spruce community types (tables 6, 7, 9; fig. 9). The logging debris covered only 50 percent of the plots, whereas dead moss covered 31 percent, indicating much less physical disturbance of the forest floor. Surviving live mosses, primarily the original feathermoss, *Hylocomium*

splendens, retained an average cover of 3 percent and was able to expand rapidly in the first year, probably because of the shading effect of the residual trees. The tall shrub layer, especially alders and roses, remained partially intact.

Figure 9—**A.** Open white spruce/thinleaf alder/feathermoss type (unit 14) before logging.

Figure 9—**B.** The same location in June 1983, the first summer after a shelterwood treatment at a 9-m spacing.

Figure 9–C. A 1-m^2 plot before logging in unit 14.

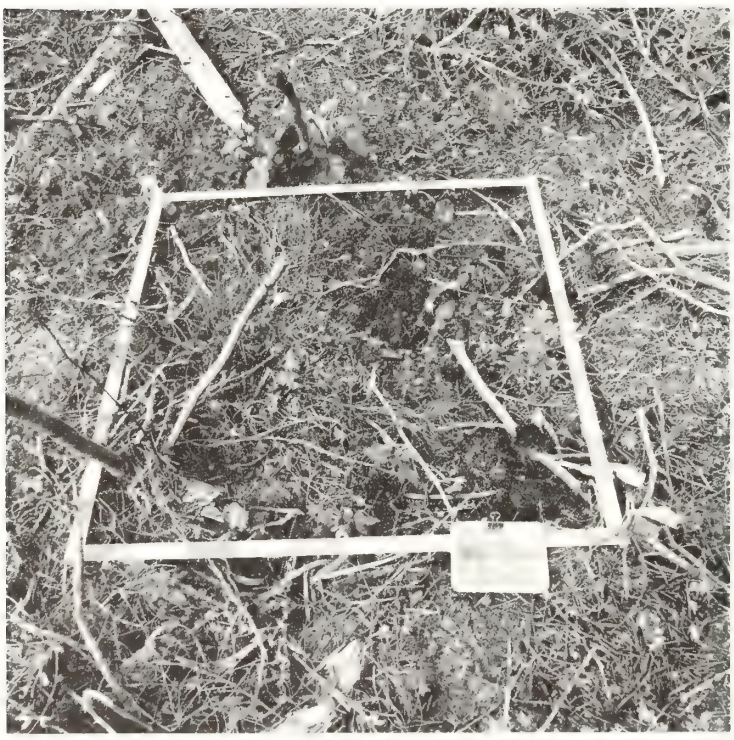


Figure 9—D. The same 1-m^2 plot in June 1983, the first summer after the shelterwood treatment.

Recovery of shrubs, herbs, and mosses during the two summers after logging was most rapid in the units with the 9-m residual tree spacing shelterwood treatment. *Rosa acicularis, Calamagrostis canadensis*, and *Cornus canadensis* had equaled or doubled their pretreatment cover values; *Alnus crispa, A. tenuifolia, Linnaea borealis, Vaccinium vitis-idaea, Equisetum arvense, Mertensia paniculata, Pyrola asarifolia,* and *Hylocomium splendens* made substantial increases toward regaining their pretreatment values. Many of the latter species have cover values of nearly half of their former levels.

Enough disturbance occurred to the sites to eliminate some species such as *Boschniakia rossica, Elymus alaskanus* (Scriebn. & Merr.) A. Löve, and *Goodyera repens,* and to greatly reduce others, such as *Moneses uniflora, Platanthera obtusata,* and many moss species. Some sites were available for invasion by new species: *Populus balsamifera, P. tremuloides, Rubus idaeus, Salix novae-angliae, Epilobium angustifolium, E. hornemannii* Rehbn., *Galium trifidum, Poa* sp., *Stellaria longipes,* and *Marchantia polymorpha* were found in the plots in 1984 but had not been present before logging.

The 9-m spacing shelterwood treatment had less impact on vegetation than did the other treatments. Species dominant before the treatment remained among the important species 2 years after logging.

Thinning plots--In addition to the two shelterwood treatments, a series of thinning plots was established in a dense, closed stand of white spruce (fig. 1, units A-L). The effects of the treatment were essentially the same as those for the 9-m spacing shelterwood so are not given in detail here or in the tables.

Conclusions

Forests on the flood plain of many Alaska rivers are the result of primary succession; that is, plant communities develop on sites not previously supporting vegetation. Logging on these sites results in subsequent changes in the forest community best described as secondary succession. One important aspect of our research was to learn more about the differences and similarities in forest development between primary and secondary succession on these sites. A remarkable feature of secondary succession is the invasion of aspen after harvesting and site preparation. Aspen is common on many of the units, especially the clearcut and burned sites. The species occurs only rarely in primary succession on these sites and then only in the seedling stage. The seed source for aspen is upland sites several kilometers from Willow Island. Following the fate of aspen on these sites will be especially interesting.

A decline in the site quality of white spruce stands occurs as these stands mature (Viereck 1970). This appears to be true for Willow Island, where dominant trees on older parts of the island exhibited markedly different height-growth patterns from those of young stands (Zasada 1984). The significant factor in this decline appeared to be closely related to a decrease in soil temperature as white spruce stands mature and the forest floor increases in thickness and insulating properties. Forest harvesting and site preparation have caused a significant increase in soil temperature, at least in the short term.

On Willow Island, Salchaket soils are warmest. The intermittent-frost phase of the Salchaket is intermediate in temperature; the Tanana soils, with continuous permafrost, are coldest.

In the subarctic, soil temperatures are important in controlling the distribution and productivity of forest communities. In summing up the results of their 5-year, interdisciplinary study, Van Cleve and Dyrness (1983) stated:

> Results of the research program indicate that taiga forest ecosystem structure and function largely are mediated by forest floor and mineral soil temperature. Black spruce, the forest type which displays lowest productivity and rates of nutrient cycling, occupies sites with the coldest soils. The most productive forest types, those which display most rapid nutrient cycling, are encountered on warmer soils.

An important consideration in any forest management strategy in interior Alaska is the impact on soil temperatures. Practices that increase soil warming may considerably increase the productive capacity of the site. In this study, we were able to assess the effects of clearcutting and the shelterwood silvicultural systems in white spruce stands on understory vegetation and soil temperatures. Not surprisingly, clearcutting followed by broadcast slash burning resulted in the most marked changes in vegetation and soil temperature. The slash fires burned under fairly dry conditions and consumed almost all available fuels. Many plant species present before disturbance were absent for the first 3 years after treatment. Inventories of permanent plots showed that 17 plant species were eliminated by logging and burning. The postdisturbance vegetation was sparse and dominated by invading species, such as *Ceratodon purpureus* and *Epilobium angustifolium,* and deep-rooted species, such as *Equisetum arvense* and *Rosa acicularis.* Seedbeds resulting from this treatment favored the germination of deciduous tree species; *Populus tremuloides, P. balsamifera*, and *Betula papyrifera* seedlings were common.

Removal of the vegetation and blackening of the soil surface by logging and burning resulted in spectacular increases in soil temperature. In the most outstanding case, soil temperatures were almost twice as high in the treated areas as they were in a nearby undisturbed control (as evaluated by soil degree-day values measured at a depth of 10 cm). As a result of this substantial soil warming, permafrost present before disturbance was gone from the soil profile by the second year after logging. The soil warming measured on this plot (which caused the plot to be almost three times as warm as the control at the 20-cm depth) is probably the maximum that could be expected as a result of a logging treatment.

Clearcutting without slash burning had less impact on the soil and vegetation. Although the trees were removed, many of the species in the understory remained in the stand after logging. We expect, however, that these residual species will be dominated over time by faster growing, more light-tolerant plants. Tree seedlings germinating and surviving on bare mineral soil were mostly *Populus balsamifera* and *Betula papyrifera.* Only a few white spruce seedlings were present.

Because of the remaining forest floor insulation and vegetative cover on clearcut sites, soil temperature increases were less than one-half those measured in areas clearcut and burned. The average increase in soil temperature in clearcuttings as compared to the undisturbed controls was 29 percent at a depth of 10 cm and 73 percent at 20 cm. Although these increases are smaller than with burning, they are still significant and suggest some substantial increases in site productivity.

The effects of the shelterwood treatments on the vegetation were minimal. Apparrently removing some of the trees from a winter snowpack, combined with leaving partial overstory shade, results in preserving the characteristics of most of the preexisting vegetation. The only species present before disturbance, but absent after logging, were delicate, shade-loving herbs such as *Goodyera repens, Calypso bulbosa*, and *Cypripedium passerinum* Richards. The dominant prelogging species remained and, at the end of the third year after logging, were beginning to expand their coverage. White spruce seedlings were more abundant in the shelterwoods than in the clearcuts; those that survived logging appeared to be thriving.

Increases in soil temperature caused by shelterwood harvesting were somewhat less than those resulting from clearcutting. The differences were not great though. At the end of the third growing season after logging, soil temperatures had increased 58 percent at the 20-cm depth in shelterwoods vs. 73 percent in clearcuts. Despite some residual overstory shade, disturbance from creating shelterwoods is apparently sufficient for substantial soil warming.

The thinning treatment appeared to have the least impact on vegetation and soils, as we had expected. For the most part, no major vegetative changes were encountered. Unfortunately, the felled trees were left lying on some plots for several months, thereby allowing the buildup of a spruce beetle (Coleoptera: Scolytidae) population. The beetles attacked the residual trees, and tree mortality is expected to cause additional, serious site changes in the future. The thinning operation apparently did cause a small increase in soil temperatures. Figures for 1985 showed a 12-percent increase at the 10-cm depth and a 20-percent increase at 20 cm. These figures represent only a small sample, however, with only one thinned plot studied.

Acknowledgments

We greatly appreciate the help of Kristine Benson, Arlene Davis, and Jim MacCracken during the data collection phase of this study. Their personal interest and attention to detail were essential to the successful completion of the work.

References

Cottam, G.; Curtis, J.T. 1956. The use of distance measures in phytosociological sampling. Ecology. 37(3): 451-460.

Foote, M. Joan. 1983. Classification, description, and dynamics of plant communities after fire in the taiga of interior Alaska. Res. Pap. PNW-307. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 108 p.

Ganns, Richard C. 1977. Germination and survival of artificially seeded white spruce on prepared seedbeds on an interior Alaskan floodplain site. Fairbanks: University of Alaska. 81 p. M.S. thesis.

Juday, Glenn P.; Zasada, John C. 1984. Structure and development of an old-growth white spruce forest on an interior Alaska floodplain. In: Meehan, William R.; Merrell, Theodore R. Jr., Hanley, Thomas A. eds. Fish and wildlife relationships in old-growth forests; Proceedings of a symposium; 1982 April 12-15; Juneau, AK. Morehead City, NC: American Institute of Fishery Research Biologists: 227-234.

Krasny, M.E. 1986. Establishment of four Salicaceae species on riverbars along the Tanana, Alaska. Seattle: University of Washington. 152 p. Ph.D. dissertation.

In the subarctic, soil temperatures are important in controlling the distribution and productivity of forest communities. In summing up the results of their 5-year, interdisciplinary study, Van Cleve and Dyrness (1983) stated:

> Results of the research program indicate that taiga forest ecosystem structure and function largely are mediated by forest floor and mineral soil temperature. Black spruce, the forest type which displays lowest productivity and rates of nutrient cycling, occupies sites with the coldest soils. The most productive forest types, those which display most rapid nutrient cycling, are encountered on warmer soils.

An important consideration in any forest management strategy in interior Alaska is the impact on soil temperatures. Practices that increase soil warming may considerably increase the productive capacity of the site. In this study, we were able to assess the effects of clearcutting and the shelterwood silvicultural systems in white spruce stands on understory vegetation and soil temperatures. Not surprisingly, clearcutting followed by broadcast slash burning resulted in the most marked changes in vegetation and soil temperature. The slash fires burned under fairly dry conditions and consumed almost all available fuels. Many plant species present before disturbance were absent for the first 3 years after treatment. Inventories of permanent plots showed that 17 plant species were eliminated by logging and burning. The postdisturbance vegetation was sparse and dominated by invading species, such as *Ceratodon purpureus* and *Epilobium angustifolium,* and deep-rooted species, such as *Equisetum arvense* and *Rosa acicularis.* Seedbeds resulting from this treatment favored the germination of deciduous tree species; *Populus tremuloides, P. balsamifera*, and *Betula papyrifera* seedlings were common.

Removal of the vegetation and blackening of the soil surface by logging and burning resulted in spectacular increases in soil temperature. In the most outstanding case, soil temperatures were almost twice as high in the treated areas as they were in a nearby undisturbed control (as evaluated by soil degree-day values measured at a depth of 10 cm). As a result of this substantial soil warming, permafrost present before disturbance was gone from the soil profile by the second year after logging. The soil warming measured on this plot (which caused the plot to be almost three times as warm as the control at the 20-cm depth) is probably the maximum that could be expected as a result of a logging treatment.

Clearcutting without slash burning had less impact on the soil and vegetation. Although the trees were removed, many of the species in the understory remained in the stand after logging. We expect, however, that these residual species will be dominated over time by faster growing, more light-tolerant plants. Tree seedlings germinating and surviving on bare mineral soil were mostly *Populus balsamifera* and *Betula papyrifera.* Only a few white spruce seedlings were present.

Because of the remaining forest floor insulation and vegetative cover on clearcut sites, soil temperature increases were less than one-half those measured in areas clearcut and burned. The average increase in soil temperature in clearcuttings as compared to the undisturbed controls was 29 percent at a depth of 10 cm and 73 percent at 20 cm. Although these increases are smaller than with burning, they are still significant and suggest some substantial increases in site productivity.

The effects of the shelterwood treatments on the vegetation were minimal. Apparrently removing some of the trees from a winter snowpack, combined with leaving partial overstory shade, results in preserving the characteristics of most of the preexisting vegetation. The only species present before disturbance, but absent after logging, were delicate, shade-loving herbs such as *Goodyera repens, Calypso bulbosa*, and *Cypripedium passerinum* Richards. The dominant prelogging species remained and, at the end of the third year after logging, were beginning to expand their coverage. White spruce seedlings were more abundant in the shelterwoods than in the clearcuts; those that survived logging appeared to be thriving.

Increases in soil temperature caused by shelterwood harvesting were somewhat less than those resulting from clearcutting. The differences were not great though. At the end of the third growing season after logging, soil temperatures had increased 58 percent at the 20-cm depth in shelterwoods vs. 73 percent in clearcuts. Despite some residual overstory shade, disturbance from creating shelterwoods is apparently sufficient for substantial soil warming.

The thinning treatment appeared to have the least impact on vegetation and soils, as we had expected. For the most part, no major vegetative changes were encountered. Unfortunately, the felled trees were left lying on some plots for several months, thereby allowing the buildup of a spruce beetle (Coleoptera: Scolytidae) population. The beetles attacked the residual trees, and tree mortality is expected to cause additional, serious site changes in the future. The thinning operation apparently did cause a small increase in soil temperatures. Figures for 1985 showed a 12-percent increase at the 10-cm depth and a 20-percent increase at 20 cm. These figures represent only a small sample, however, with only one thinned plot studied.

Acknowledgments

We greatly appreciate the help of Kristine Benson, Arlene Davis, and Jim MacCracken during the data collection phase of this study. Their personal interest and attention to detail were essential to the successful completion of the work.

References

Cottam, G.; Curtis, J.T. 1956. The use of distance measures in phytosociological sampling. Ecology. 37(3): 451-460.

Foote, M. Joan. 1983. Classification, description, and dynamics of plant communities after fire in the taiga of interior Alaska. Res. Pap. PNW-307. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 108 p.

Ganns, Richard C. 1977. Germination and survival of artificially seeded white spruce on prepared seedbeds on an interior Alaskan floodplain site. Fairbanks: University of Alaska. 81 p. M.S. thesis.

Juday, Glenn P.; Zasada, John C. 1984. Structure and development of an old-growth white spruce forest on an interior Alaska floodplain. In: Meehan, William R.; Merrell, Theodore R. Jr., Hanley, Thomas A. eds. Fish and wildlife relationships in old-growth forests; Proceedings of a symposium; 1982 April 12-15; Juneau, AK. Morehead City, NC: American Institute of Fishery Research Biologists: 227-234.

Krasny, M.E. 1986. Establishment of four Salicaceae species on riverbars along the Tanana, Alaska. Seattle: University of Washington. 152 p. Ph.D. dissertation.

Krasny, M.E.; Vogt, K.A.; Zasada, J.C. 1984. Root and shoot biomass and mycorrhizal development of white spruce seedlings naturally regenerating in interior Alaska floodplain communities. Canadian Journal of Forest Research. 14: 554-558.

Ohmann, Lewis L.; Ream, R.R. 1971. Wilderness ecology: a method of sampling and summarizing data for plant community classification. Res. Pap. NC-49. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 14 p.

Putman, W.E.; Zasada, J.C. 1986. Direct seeding techniques to regenerate white spruce in interior Alaska. Canadian Journal of Forest Research. 16: 660-664.

Rieger, Samuel; Dement, James A.; Sanders, Dupree. 1963. Soil survey of Fairbanks area, Alaska. Washington, DC: U.S. Department of Agriculture, Soil Conservation Service. 41 p.

Soil Survey Staff. 1951. Soil survey manual. Agric. Handb. 18. Washington, DC: U.S. Department of Agriculture. 503 p.

Van Cleve, K.; Dyrness, C.T. 1983. Conclusions and direction for future research in taiga forest ecosystems. Canadian Journal of Forest Research. 13(5): 914-916.

Van Cleve, Keith; Dyrness, Ted; Viereck, Les. 1980. Nutrient cycling in interior Alaska flood plains and its relationship to regeneration and subsequent forest development. In: Murray, M.; Van Veldhuizen, R.M., eds. Forest regeneration at high latitudes; Proceedings, international workshop, 1979 November 15-17; Fairbanks, AK. Gen Tech. Rept. PNW-107. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station: 11-18.

Van Cleve, Keith; Viereck, Leslie A. 1981. Forest succession in relation to nutrient cycling in the boreal forest of Alaska. In: West, Darrell C.; Shugart, Herman H.; Botkin, Daniel B., eds. Forest succession concepts and application. New York: Springer-Verlag: 185-211.

Viereck, L.A. 1970. Forest succession and soil development adjacent to the Chena River in interior Alaska. Arctic and Alpine Research. 2: 1-26.

Viereck, L.A.; Dyrness, C.T.; Batten, A.R. Revision of preliminary classification for vegetation of Alaska. Fairbanks, AK: Institute of Northern Forestry. Unpublished Report. 141 p. Written in 1986.

Viereck, Leslie A.; Dyrness, C.T.; Van Cleve, Keith; Foote, M. Joan. 1983. Vegetation, soils and forest productivity in selected forest types in interior Alaska. Canadian Journal of Forest Research. 13(5): 703-720.

Walker, L.R.; Zasada, J.C.; Chapin, F.S., III. 1986. The role of life history processes in primary succession on an Alaskan floodplain. Ecology. 67(5): 1243-1253.

Zasada, J.C. 1984. Site classification regeneration practices of floodplain sites in interior Alaska. In: Murray, M. ed. Forest classification at high latitudes as an aid to regeneration. Gen. Tech. Rep. PNW-177. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station: 35-39.

Zasada, John; Norum, Rodney. 1986. Prescribed burning white spruce slash in interior Alaska. Northern Journal of Applied Forestry. 3(1): 16-18.

Zasada, John C.; Slaughter, Charles W.; Argyle, J. Dean [and others]. 1987. Winter logging on the Tanana River flood plain in interior Alaska. Northern Journal of Applied Forestry. 4: 11-16.

Dyrness, C.T.; Viereck, L.A.; Foote, M.J.; Zasada, J.C. The effect on vegetation and soil temperature of logging flood-plain white spruce. Res. Pap. PNW-RP-392. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station; **1988.** 45 p.

During winter 1982-83, five silvicultural treatments were applied on Willow Island (near Fairbanks, Alaska): two types of shelterwood cuttings, a clearcutting, a clearcutting with broadcast slash burning, and a thinning. The effects of these treatments on vegetation, soil temperature, and frost depth were followed from 1983 through 1985. In 1984 and 1985, logged plots had significantly higher soil temperatures than did the controls; clearcut and burned sites had the greatest increases. Vegetation composition was profoundly changed on the clearcut and burned units and altered to a lesser extent on the units receiving the other treatments.

Keywords: Alaska, succession, forest communities, site preparation, soil series.

The **Forest Service** of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing Nation.

The U.S. Department of Agriculture is an Equal Opportunity Employer. Applicants for all Department programs will be given equal consideration without regard to age, race, color, sex, religion, or national origin.

Pacific Northwest Research Station
319 S.W. Pine St.
P.O. Box 3890
Portland, Oregon 97208

April 1988

U.S. Department of Agriculture
Pacific Northwest Research Station
319 S.W. Pine Street
P.O. Box 3890
Portland, Oregon 97208

BULK RATE
POSTAGE +
FEES PAID
USDA-FS
PERMIT No. G-40

Official Business
Penalty for Private Use, $300

do NOT detach label

United States
Department of
Agriculture

Forest Service

Pacific Northwest
Research Station

Research Paper
PNW-RP-393

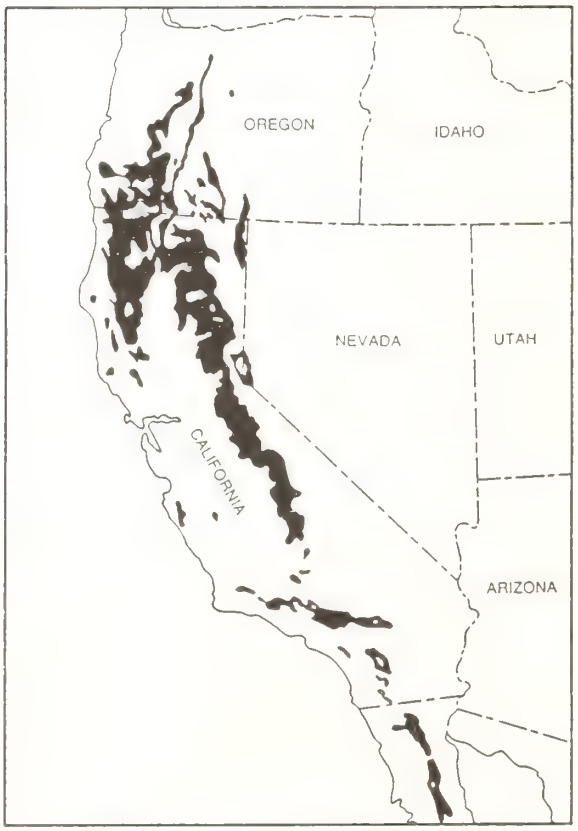
Lumber Recovery From Incense-Cedar in Central California

JUL 1968

W.Y. Pong and James M. Cahill

THE TREE—The range of incense-cedar extends from the southern slopes of Mount Hood in Oregon south through the Cascade Range, Siskiyou Mountains, Coast Range, and Sierra Nevada to the Sierra San Pedro Martir in Baja California. It grows at increasingly higher elevations toward the southern part of its range. Incense-cedar seldom grows in pure stands; it is generally intermingled with ponderosa pine, sugar pine, Douglas-fir, and white fir. Incense-cedar trees are long lived; large trees are often more than 500 years old. Mature trees have thick, fibrous, light brown or reddish bark that becomes deeply furrowed (see cover). Under average conditions, mature trees are 20-30 inches in diameter and 75-110 feet tall.

THE WOOD—The wood of incense-cedar is nonresinous. Sapwood is white or cream colored, and the heartwood is light brown or reddish brown. Annual rings are moderately distinct and usually measure 20-30 per inch in average material. Incense-cedar wood is exceptionally resistant to decay and highly durable when exposed to weather. It also has high dimensional stability; volumetric shrinkage is only 3.8 percent when the wood is dried from a green state down to 12-15 percent moisture content. Incense-cedar wood is noted for its ease of machining to a smooth, even finish. Because it adheres well under virtually every gluing condition, it is commonly used for pencil stock. Incense-cedar wood weighs about 24 pounds per cubic foot at 12 percent moisture content and has a specific gravity of 0.37.



Natural range of incense-cedar.

Authors

W.Y. PONG was a research forest-products technologist (now retired) and JAMES M. CAHILL is a research forester, Forestry Sciences Laboratory, P.O. Box 3890, Portland, Oregon 97208-3890.

Abstract

Pong W.Y.; Cahill, James M. 1988. Lumber recovery from incense-cedar in central California. Res Pap. PNW-RP-393. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 22 p.

A sample of 130 incense-cedar (*Libocedrus decurrens* Torr.) trees was selected from the Eldorado National Forest in California. The trees were felled and bucked into 403 woods-length logs and processed through a sawmill cutting Shop and Common grades of lumber. Recovery estimates are shown for woods-length logs based on Scribner board-foot scale and cubic-foot scale. Analysis showed that board-foot recovery ranged from 169 percent for 6-inch logs to 103 percent for 34-inch logs. Cubic-volume recovery of rough green lumber increased from 50 percent to 62 percent for the same range of diameters. Yields of higher quality lumber (Shops and Moulding) increased as log diameter increased. Percentage of Scribner scaled defect was found to be correlated with several measures of product recovery.

Keywords: Lumber recovery, lumber value, incense-cedar, log scale, California.

Summary

This report presents lumber-recovery data for 130 incense-cedar trees selected from the Sierra Nevada of central California. Over 400 woods-length logs were processed through a sawmill cutting Shop and Common grades of lumber. Diameter of the study logs ranged from 6 to 34 inches. The average defect was from 4 to 17 percent Scribner and 3 to 10 percent cubic scale. Lumber recovery is presented on the basis of both board feet and cubic feet.

Several measures of product recovery were correlated with scaling diameter. Regression models were developed for the following variables:

- Board-foot recovery percent;
- Cubic recovery percent of lumber, sawdust, and chips;
- Board foot of lumber per cubic foot of lumber;
- Percent lumber-grade recovery; and
- Dollars per thousand board feet lumber tally ($/MLT).

Board-foot recovery percent decreased as log diameter increased; values ranged from 169 percent for 6-inch logs to 103 percent for 34-inch logs. Cubic lumber-recovery percent increased rapidly in the smaller logs (6-14 inches), leveled off in the midsize logs (16-24 inches), and decreased slightly for logs over 24 inches. Board foot of lumber per cubic foot of lumber decreased with increasing log size because 6/4-inch lumber items were cut oversized to allow remanufacture into alternate products. Larger logs produced a greater proportion of 6/4 lumber. The average lumber value ($/MLT) increased with increasing log diameter because of the production of highly valued lumber items (Shops and Moulding) from the larger logs. Lumber values are based on 1985 prices; two methods that allow users to update the $/MLT to future prices are presented.

The percentage of Scribner scaling defect was correlated with board-foot recovery percent and $/MLT. As defect percent increased, board-foot recovery percent increased and $/MLT decreased.

Log values were computed indirectly from previously defined recovery ratios. Dollars per thousand board feet of net log scale decreased for logs up to 14 inches and then increased. Dollars per hundred cubic feet of cubic product scale increased with increasing log size.

Factors for converting Scribner log scale to cubic log scale were computed for gross and net scales. Conversion factors were correlated with scaling diameter; the ratio of board feet to cubic feet increased as log size increased.

Contents

1 **Introduction**

1 **Methods**

1 Sample Selection

1 Harvesting and Scaling

3 Processing

4 **Analysis**

4 Independent Variables

4 Dependent Variables

5 **Results and Discussion**

5 Volume Recovery

9 Lumber-Grade Recovery

11 Value Recovery

14 Direct Product Estimators

14 Log-Scale Conversion Factors

17 **Metric Equivalents**

18 **Literature Cited**

19 **Appendix 1**

20 **Appendix 2**

22 **Appendix 3**

Introduction

Incense-cedar (*Libocedrus decurrens* Torr.) is an important commercial softwood species in the Western United States. Currently about 14 billion board feet of commercial-size incense-cedar are growing in the West with the majority of volume (72 percent) in California (USDA Forest Service 1973b). Incense-cedar wood is manufactured into many products including lumber, pencil stock, fence posts, and shakes.

The major objective of this study was to determine the volume and value of lumber from incense-cedar trees. This research provides managers of both public and private timberlands with the basic data they need to estimate the lumber volume and grade recovery from this species. Results of the study can also be used by loggers, sawmill operators, timber growers, and forest administrators for other activities including log allocation, mill design, and equipment evaluation.

This study was a cooperative effort by the Pacific Northwest Research Station (PNW), the Pacific Southwest Region of the National Forest System, and the Wetsel-Oviatt Lumber Company of Shingle Springs, California.

The data summarized in this publication are available from PNW on a 5-1/4-inch diskette. Readers can receive this information by sending a double-sided, double density diskette to the Pacific Northwest Research Station, Timber Quality Project, P.O. Box 3890, Portland, OR 97208-3890. A listing of the data format is shown in appendix 1.

Methods

Sample Selection

A total of 130 incense-cedar trees were selected from six areas in the Eldorado National Forest (fig. 1). Trees were selected to represent the range of size and quality in incense-cedar. Sample trees ranged from 10 to 54 inches in diameter at breast height (DBH).[1] Tree quality was based on Pacific Southwest Region Dinuba Grades (Wise and May 1958) as applied to the first 16-foot log in the tree. Table 1 shows the distribution of sample trees by tree DBH, tree height classes, and the Dinuba Grades

We should emphasize that the sample reflected the range of size and quality existing in incense-cedar and provides a base for predicting the volume and value of similar trees or logs. The sample was not selected to produce the mix of log sizes and grades normally found in a mill.

Harvesting and Scaling

Trees were felled and bucked in accordance with normal industry practices. Each log was identified by tree number and position of the log within the tree. This number was used to identify lumber items sawn from a specific log. Study logs were trucked to the cooperating mill where they were scaled. Scribner scale was taken by USDA Forest Service check scalers according to the National Forest Log Scaling Handbook (USDA Forest Service 1973a).[2] Cubic scale was taken in conformance with the draft of the proposed cubic scaling handbook.[3] The number of logs and the average percentage of Scribner and cubic scaling defect is shown by Scribner scaling diameter in table 2.

---

[1] Diameter of the tree at 4-1/2 feet above the ground as measured on the uphill side of the tree

[2] The rules for scaling pecky rot were modified in this study. Pockets of rot were squared out and deducted only if they were less than 4-1/2 inches apart; all other pockets were ignored.

[3] USDA Forest Service cubic scaling handbook (review draft). 1978. Washington, DC: U.S. Department of Agriculture, Forest Service. 192 p

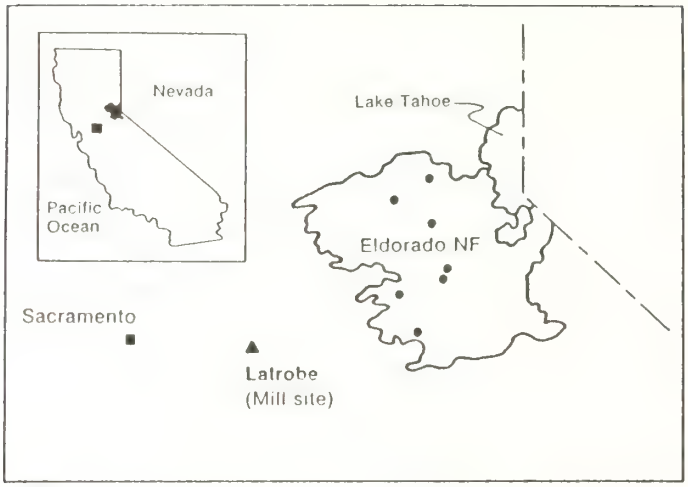


Figure 1—Approximate locations where trees were selected in the Eldorado National Forest, California, and the mill location.

Table 1—Number of incense-cedar trees by DBH class, height range, and butt-log grade

DBH class	Height range[a]	Butt-log grade[b]				
		1	2	3/4[c]	9[d]	Total
Inches	*Feet*	*Number of Trees*				
10.6-15.5	27- 56	0	0	10	0	10
15.6-20.5	39- 67	1	4	15	0	20
20.6-25.5	49- 94	0	4	11	2	17
25.6-30.5	60-112	2	8	3	4	17
30.6-35.5	70-130	3	10	1	0	14
35.6-40.5	67-130	8	10	0	2	20
40.6-45.5	54-125	4	5	0	4	13
45.6-50.5	101-144	8	4	0	2	14
50.6-55.5	112-142	4	1	0	0	5
Total		30	46	40	14	130

[a] Tree height above a 1-foot stump.
[b] Pacific Southwest Region Dinuba grades applied to 16-foot butt log (Wise and May 1958).
[c] Trees with these butt-log grades were combined into one grade group.
[d] Trees with cull butt logs but with merchantable upper logs.

Table 2—Number of woods-length incense-cedar logs, by scaling diameter and the average percent Scribner and cubic log-scale defect

Scaling diameter	Number of logs	Defect	
		Scribner	Cubic
Inches		*Percent*	
6- 8	83	4.0	3.0
9-10	32	10.7	4.0
11-12	47	7.8	4.1
13-14	34	7.3	3.2
15-16	42	7.1	6.2
17-18	26	9.9	5.3
19-20	33	11.4	3.8
21-22	35	11.6	7.8
23-24	20	12.2	4.3
25-26	10	11.5	9.5
27-28	21	12.0	6.5
29-30	9	17.0	5.8
31-32	5	9.5	4.3
33-34	6	13.0	8.8
Total or average	403	8.7	4.8

Gross cubic-foot volume of butt logs was estimated using an equation developed by Bruce (1982):

$$\text{Cubic-foot volume} = 0.005454L\ (0.75\ SD^2 + 0.25\ LD^2)\ .$$

Smalian's formula was used to compute gross cubic-foot volume for all other logs:

$$\text{Cubic foot volume} = 0.005454L\ \frac{(SD^2 + LD^2)}{2}\ ,$$

where L is log length in feet,
SD is the small-end diameter in inches,
LD is the large-end diameter in inches, and
0.005454 is a conversion constant.

Cubic product scale is defined as the gross cubic-foot volume reduced for all defects expected to affect the yield of solid-wood products.

Processing

Study logs were sawn by the Wetsel-Oviatt Lumber Company mill near Latrobe, California. Milling conformed to the general industry practice of sawing each log for maximum lumber volume consistent with the recovery of the highest lumber-grade yield. Production equipment in the sawmill included a ring debarker, single-cut band headsaw, single-band vertical resaw, double arbor edger, and a trim saw. Lumber is sorted from the green chain with an edge-drop sorter, and stickered or stacked, or both, with two mobile stickering machines.

All lumber met the standards of the national grading rules for softwood lumber and appropriate regional rules as published by the Western Wood Products Association (WWPA 1981). Grading of all lumber items was supervised by a WWPA grade inspector. The mill normally kiln dries incense-cedar Shops, and Moulding and Selects, but not the Commons. Not all lumber was graded in the same condition: Moulding and Selects were graded rough dry, Shops were graded surfaced two sides, and Commons were graded rough green. Lumber dimensions, grade, and tree-log identification number of each lumber item were tallied after grading. Eleven grades of lumber were produced during the study; for ease of presentation, they were combined into five grade groups:

Grade group	Lumber grades
Moulding and Better (Mldg & Btr)	Selects Moulding
Shops	Factory Select/3 clear 1,2,3 Shop Shop outs
3 and Better Common (3 & Btr Com)	1,2,3 Common
4 Common	4 Common
5 Common	5 Common

Analysis

The purpose of the analysis was to develop, for woods-length logs, regression equations predicting:

1. The volume yield of primary (lumber) and secondary products (sawdust and chips).
2. Grade recovery of lumber.
3. Lumber and log values.

Independent Variables

Log diameter—Scribner scaling diameter (D) and transformations of D were used as independent variables to find the best equation for each dependent variable. Inverse polynomial curves, which were found useful in modeling lumber recovery data in other studies (Snellgrove and Cahill 1980), were applied. A final curve for each dependent variable was selected based on the model with the highest coefficient of determination (R^2).

Defect—When possible, regression models were developed by using the percentage of log defect as an additional independent variable. Defect percent was computed using Scribner and cubic log-scale estimates of defect volume.

Direct product estimators—Cubic product scale was used as a direct product estimator to predict the cubic-foot volume of lumber, sawdust, and chips (Fahey 1983).

Dependent Variables[4]

Regression models were developed for the following dependent variables:

Product-volume recovery—
1. Board-foot recovery percent.
2. Cubic recovery percent (lumber, sawdust, and chips).
3. The ratio of board feet of lumber to cubic feet of lumber (BF/CF Lum).

Lumber-grade recovery—
The volume of lumber recovered in each lumber-grade group was expressed as a cumulative percentage of the total lumber volume in the log.

Value recovery—
1. Lumber value in dollars per thousand board feet lumber tally ($/MLT).
2. Log value in dollars per thousand board feet of net Scribner log scale ($/MNLS).
3. Log value in dollars per hundred cubic feet of cubic product scale ($/CCF).

Log-scale conversion factors—
1. Ratio of gross Scribner log scale to gross cubic-foot log scale (BF/CF Log Gross).
2. Ratio of net Scribner log scale to cubic product scale (BF/CF Log Net).

[4] Dependent variables are defined in appendix 2.

Results and Discussion

Volume Recovery

Board-foot recovery percent—Overrun is a common term used to describe the percentage of lumber recovered (board-foot tally) in excess of Scribner net log scale. Recovery percent, often confused with overrun, is the ratio of lumber tally to net log scale expressed as a percentage. A recovery percent of 150 is equivalent to an overrun of 50 percent. We will use board-foot recovery percent.

As expected, board-foot recovery percent decreased as log diameter increased (fig. 2). Recovery values ranged from a high of 169 percent for 6-inch logs to a low of 103 percent for 34-inch logs. This trend occurred because Scribner log scale underestimates the board-foot volume of small-diameter logs. Table 3 presents board-foot recovery percent for incense-cedar logs by 2-inch diameter classes.

The statistical relation between recovery percent and log diameter, although not strong ($R^2 = 0.18$), was highly significant ($P = 0.01$). These results suggest that users should estimate recovery percent of incense-cedar by diameter class rather than by using an overall average. The sample of trees selected for this study would not necessarily produce the log-diameter distributions encountered in typical commercial operations. As previously noted, selection was made to represent the size and quality available in incense-cedar from which a statistically valid base for predicting volume and value could be made.

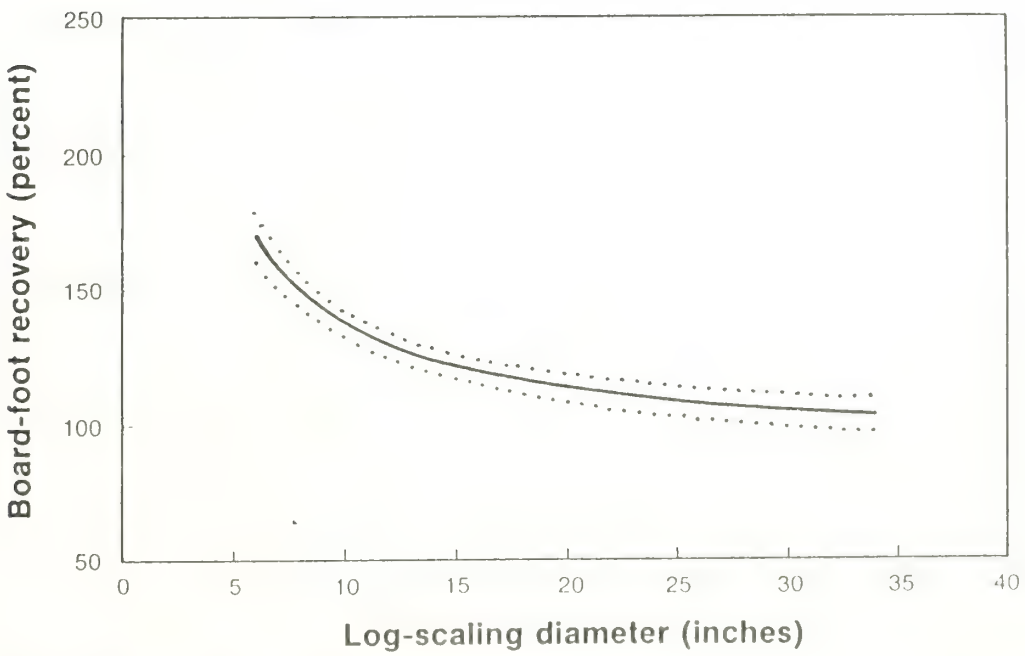


Figure 2—The relation of board-foot lumber-recovery percent (solid line) and the 95-percent confidence intervals (dashed lines) to log-scaling diameter. The regression equation is shown in appendix 3.

Table 3—Board-foot recovery percent by scaling diameter with 95-percent confidence interval (CI)

Scaling diameter	Board-foot recovery[a]	CI[b]
Inches	----- *Percent* -----	
6	169	9
8	149	6
10	137	4
12	129	4
14	123	4
16	119	4
18	116	5
20	113	5
22	111	5
24	109	6
26	107	6
28	106	6
30	105	6
32	104	6
34	103	6

[a] Regression equation listed in appendix 3.
[b] CI is the half-width of the 95-percent confidence interval for expected mean value of the dependent variable, recovery percent.

Table 4—Board-foot recovery percent by scaling diameter and percentage of Scribner scaling defect

Scaling diameter	Scribner scale defect percent					
	0	10	20	30	40	50
Inches	----- *Board-foot recovery percent*[a] -----					
6	164	168	178	195	219	249
8	142	146	156	173	197	227
10	129	133	143	160	184	214
12	121	124	134	151	175	206
14	114	118	128	145	169	199
16	110	113	123	140	164	195
18	106	109	120	137	160	191
20	103	107	117	134	158	188
22	101	104	114	131	155	186
24	99	102	112	129	153	184
26	97	101	111	128	152	182
28	96	99	109	126	150	181
30	94	98	108	125	149	179
32	93	97	107	124	148	178
34	92	96	106	123	147	177

[a] Regression equation listed in appendix 3.

Board-foot recovery percent was also correlated with the percentage of log defect, based on Scribner log scale. R^2 increased from 0.18 to 0.32 when the square of Scribner defect percent was included as an additional independent variable in the model. We found that within a diameter class, recovery percent increased as the percentage of defect increased (table 4). This was most likely due to excessive Scribner log-scale deductions that caused high recovery percents. The primary defect occurring in the study logs was pecky rot caused by the wood-rotting fungus *Polyporous amarus* Hedgc. (fig. 3). In a corollary study, Cahill and others (1987) found that Scribner scale deductions for pecky rot were excessive.

Cubic recovery percent—An accurate representation of the relation of lumber volume to log volume requires that both measures of volume be commensurable. Cubic recovery percent represents such a relation because both lumber and log volumes are accurately measured in cubic feet (Fahey and Snellgrove 1982). Figure 4 shows the percentage of cubic product scale recovered as rough green lumber, sawdust, and chips by log diameter. The curves are cumulative; that is, separate recovery-percent curves were determined, first for rough green lumber and then for rough green lumber plus sawdust. The percentage of product scale available for chips can be estimated by subtracting the cumulative percentage of rough green lumber plus sawdust from 100 percent.

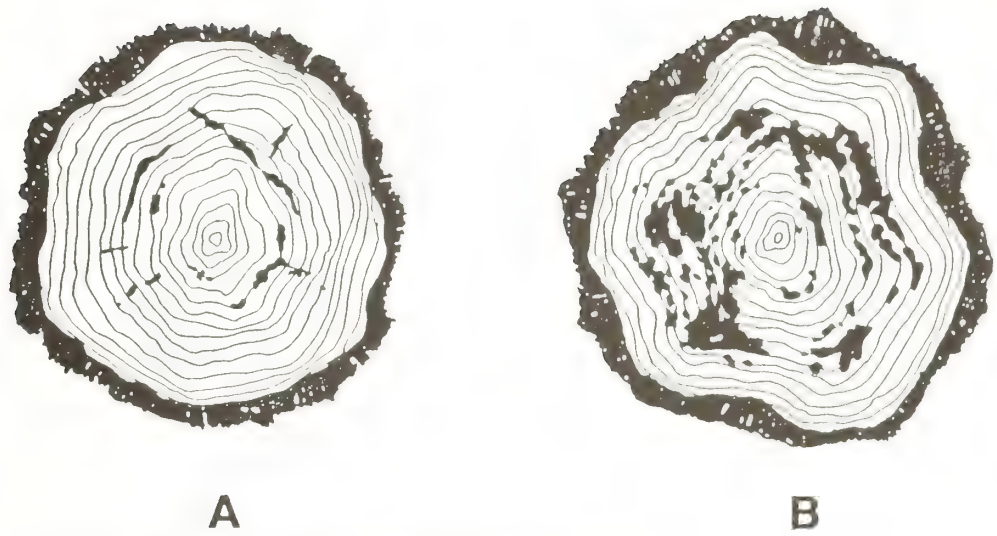


Figure 3—Incense-cedar log ends showing (A) scattered pecky rot typical of the early stages of decay, and (B) large numerous peck holes typical of advanced decay.

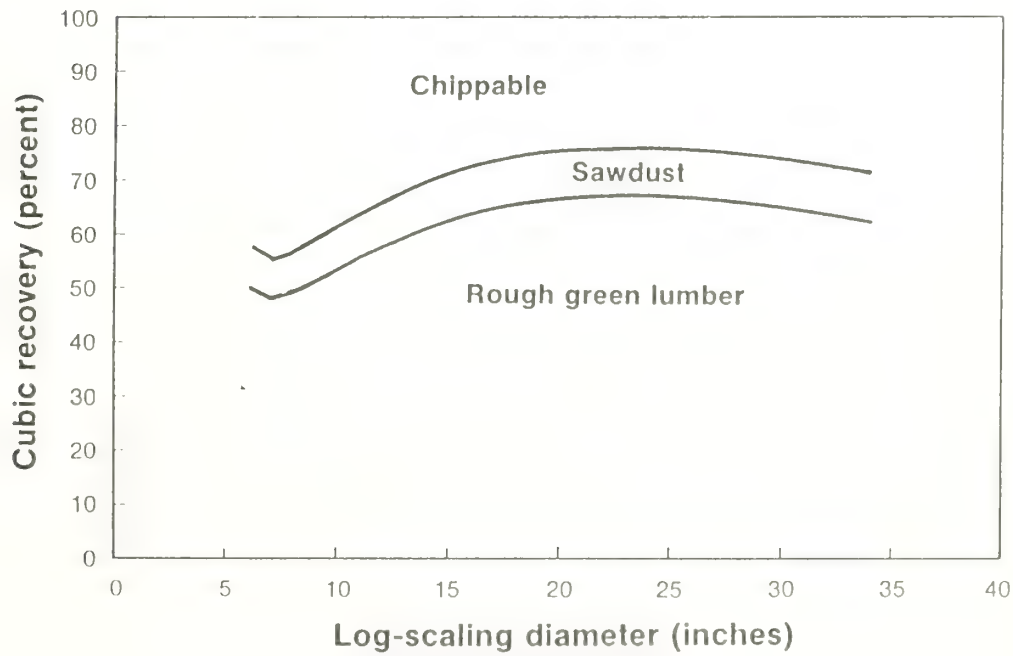


Figure 4—The relation of cubic recovery percent of rough green lumber, sawdust, and chips to log-scaling diameter. Regression equations are shown in appendix 3.

Table 5—Percent of cubic product scale manufactured into rough green lumber, sawdust, and chips, by scaling diameter[a]

Scaling diameter	Rough green lumber	Sawdust[b]	Chips[c]
Inches		*Percent*[d]	
6	50	8	42
8	49	8	43
10	53	8	39
12	57	8	34
14	61	8	31
16	63	9	28
18	65	9	26
20	66	9	25
22	67	9	24
24	67	9	24
26	66	9	24
28	66	9	25
30	65	9	26
32	64	9	27
34	62	9	28

[a] Regression equations listed in appendix 3.
[b] Percentage of sawdust calculated by subtracting the cubic recovery percent of rough green lumber from the cubic recovery percent of rough green lumber and sawdust.
[c] Percentage of chips calculated by subtracting the cubic recovery percent of rough green lumber and sawdust from 100 percent.
[d] Percentages may not total 100 because of rounding

Table 6—The ratio of board feet of lumber to cubic feet of lumber (BF/CF Lum) by scaling diameter with 95-percent confidence interval (CI)

Scaling diameter	BF/CF Lum[a]	CI[b]
Inches	*Board-foot per cubic foot*	
6	10.49	0.02
8	10.45	.01
10	10.43	.01
12	10.41	.01
14	10.40	.01
16	10.39	.01
18	10.39	.01
20	10.38	.01
22	10.38	.01
24	10.37	.01
26	10.37	.01
28	10.37	.01
30	10.37	.01
32	10.36	.01
34	10.36	.01

[a] Regression equations listed in appendix 3.
[b] CI is the half-width of the 95-percent confidence limit for the expected mean value of the dependent variable, board foot per cubic foot lumber ratio (BF/CF Lum).

Cubic recovery of lumber increased sharply in the smaller diameter logs (6-14 inches), leveled off in the midsize logs (16-24 inches), and then dropped off slightly in the larger logs (26-34 inches). The rapid rise of lumber recovery in the smaller diameter logs reflects the relative inefficiency of converting these logs into lumber. This is particularly evident in the 7- to 8-inch logs; where the cubic recovery was less than that of 6-inch logs (figure 4, table 5), suggesting that the choice of lumber items cut from the 7- to 8-inch logs did not fully use the log. The addition of cubic log-scale defect as an independent variable did not significantly improve the regressions for cubic recovery. Table 5 presents the cubic recovery percentages of lumber, sawdust, and chips by 2-inch log-diameter classes.

BF/CF Lum—The ratio of nominal board-foot volume of lumber per cubic-foot volume of rough green lumber (BF/CF Lum) is an expression frequently used in converting lumber recovery in cubic feet to board feet (Fahey and Woodfin 1976). Regression analysis showed that BF/CF Lum decreased as diameter increased. The decrease was caused by the different amounts of fiber used to produce 1-inch boards versus 6/4 lumber. At the study mill, 6/4 items were cut oversized to allow for possible remanufacture into other products. This tended to bring the average BF/CF Lum down for large logs, where a greater proportion of the lumber produced was in the 6/4 thickness. Table 6 shows the estimated BF/CF Lum by 2-inch log-diameter classes.

One important use of BF/CF Lum is to compute lumber recovery factors (LRF) (Fahey and Snellgrove 1982). LRF is defined as the board-foot volume of lumber produced from a cubic-foot volume of log. It can be estimated for any given log-diameter class by multiplying the cubic lumber-recovery percent by the BF/CF Lum. For example, LRF for a 20-inch log would be calculated as follows:

Cubic recovery percent of rough green lumber (table 5) = 66 percent;
Average BF/CF Lum (table 6) = 10.38 board feet per cubic foot lumber;
LRF = 0.66 x 10.38 = 6.85 board feet lumber per cubic foot log.

This LRF is based on a cubic product scale.

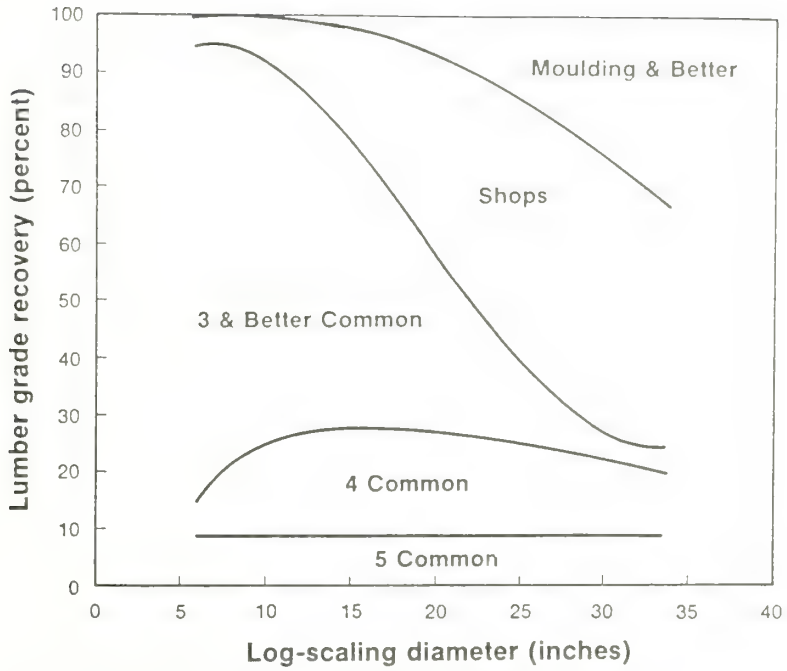


Figure 5—Cumulative percentage of volume by lumber grade. The space between the curves represents the percentage of volume for individual lumber grades. Regression equations are shown in appendix 3.

Lumber-Grade Recovery

Percentage of lumber volume by lumber grade—The cumulative percentage of lumber volume recovered in the five grade groups of lumber (see "Processing" for lumber grades in each group) was correlated with log diameter (fig. 5). As expected, a general trend occurred of increasing recovery of high-quality lumber as log diameter increased. Smaller logs produced a high proportion of Common grade lumber, and larger logs recovered greater volumes in the Shops and Moulding grades. The estimated percentages of lumber volume in each separate lumber-grade group are given in table 7. Users should be aware that these values represent general trends; a large proportion of the variation in grade yields is not accounted for by regression models with log diameter as the only independent variable.

The yield of 5 Common lumber did not vary by log diameter (fig. 5) but did increase as the percentage of Scribner log-scale defect increased (fig. 6). Much of the increase in scale defect was due to the occurrence of pecky rot in the highly defective logs. Grade 5 Common lumber sawn from these logs generally contained numerous scattered pockets of rot (peck holes).

Table 7—Percent of lumber-grade recovery by scaling diameter[a]

Scaling diameter	Lumber grade				
	5 Common	4 Common	3 and Better Common	Shops	Moulding and Better
Inches			*Percent*[b]		
6	8	7	80	6	0
8	8	13	73	6	0
10	8	17	67	8	0
12	8	19	61	12	1
14	8	19	54	17	2
16	8	20	47	23	3
18	8	19	39	29	5
20	8	19	32	35	7
22	8	18	25	40	9
24	8	17	18	44	12
26	8	16	12	48	15
28	8	15	8	49	19
30	8	14	5	50	23
32	8	13	4	47	28
34	8	12	5	43	33

[a] Regression equations listed in appendix 3.
[b] Percentages may not total 100 because of rounding.

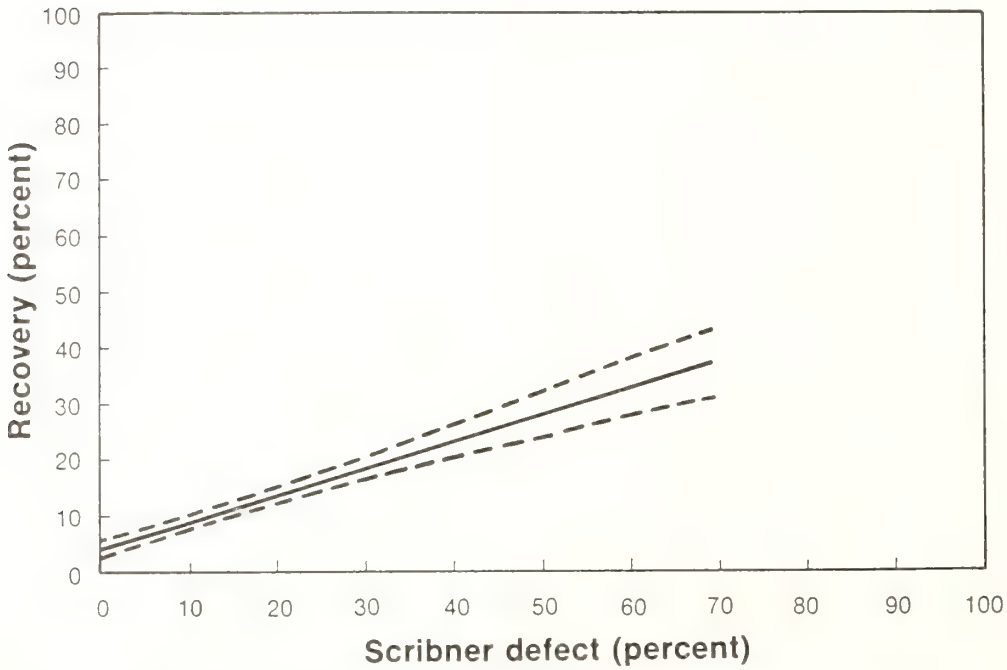


Figure 6—The relation of percent recovery of 5 Common lumber (solid line) and the 95-percent confidence intervals (dashed lines) to the percentage of Scribner scaling defect. The regression equation is shown in appendix 3.

Table 8—Lumber prices used to calculate average lumber value[a]

Lumber grade	Price per thousand board feet
	Dollars
Moulding and Better	756.24
Factory Select/3 Clear	438.25
1 Shop	441.37
2 Shop	347.14
3 Shop	272.75
Shop out	91.17
3 and Better Common	283.65
4 Common	207.79
5 Common	70.29

[a] Lumber prices are the 1985 average regional prices as supplied by USDA Forest Service, Pacific Southwest Region, San Francisco, California.

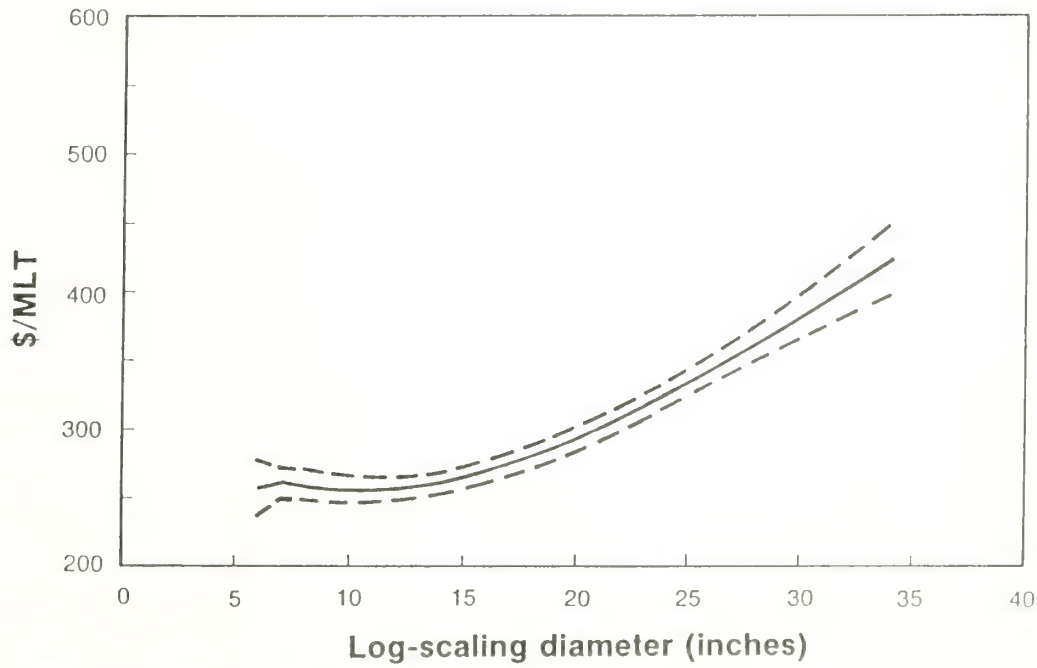


Figure 7—The relation of lumber value ($/MLT) (solid line) and the 95-percent confidence intervals (dashed lines) to scaling diameter. The regression equation is shown in appendix 3.

Value Recovery

**$/MLT**—Lumber value is determined by applying an appropriate price to the volume of each grade of lumber produced from a log. Prices we used are shown in table 8. The total value of the lumber in the log divided by the total lumber volume in thousands of board feet ($/MLT) is a useful index of log quality. Figure 7 shows that the average $/MLT increased as log diameter increased. The average lumber value for 34-inch logs, for example, is 65 percent higher than the average value for 6-inch logs. The value increase is due mainly to the greater proportion of higher value lumber produced from the larger logs. Table 9 shows the estimated $/MLT for the study logs by 2-inch log-diameter classes.

Table 9—Lumber value ($/MLT), based on 1985 prices, by scaling diameter with 95-percent confidence interval (CI)

Scaling diameter	Lumber value ($/MLT)[a]	CI[b]
Inches	*Dollars per thousand board feet*	
6	257	20
8	260	11
10	256	10
12	256	8
14	261	8
16	269	8
18	280	9
20	293	9
22	308	8
24	325	9
26	343	10
28	362	13
30	382	16
32	403	20
34	424	25

[a] Regression equation listed in appendix 3.
[b] CI is the half-width of the 95-percent confidence limit for the expected mean value of the dependent variable, lumber value ($/MLT).

Table 10—Lumber value ($/MLT), based on 1985 prices, by scaling diameter and percentage of Scribner scaling defect

Scaling diameter	Scribner scale defect percent					
	0	10	20	30	40	50
Inches	*Dollars per thousand board feet*[a]					
6	262	250	238	226	214	202
8	267	255	243	231	219	207
10	265	253	241	229	217	205
12	266	254	242	230	218	206
14	271	259	247	235	223	211
16	280	268	256	244	232	220
18	291	280	268	256	244	232
20	306	294	282	270	258	246
22	322	310	298	286	274	262
24	339	327	315	303	291	279
26	358	346	334	322	310	298
28	377	365	354	342	330	318
30	398	386	374	362	350	338
32	419	407	395	383	371	359
34	441	429	417	405	393	381

[a] Regression equation listed in appendix 3.

The lack of an appropriate log-grading system for incense-cedar precludes analyzing the relation of $/MLT vs. log diameter for individual log grades. Because of this, users should note that the averages listed in table 9 are composite values of $/MLT for all logs processed in the study and represent a wide range of log quality.

Even without a visual-grading system, we found logs can be stratified into quality classes by using the percentage of Scribner scale defect as a surrogate variable for log grade. When included as an additional independent variable in the model predicting $/MLT, defect percent increased the coefficient of determination from 0.28 to 0.36. Within a diameter class, $/MLT decreased as the percentage of defect increased. As shown earlier (fig. 6), production of low-value lumber (5 Common) increased as Scribner defect percent increased. Table 10 presents $/MLT by log diameter and percentage of scaling defect.

Repricing— A problem with $/MLT is that the lumber prices used to compute it represent a fixed point in time. Lumber prices fluctuate with supply and demand; thus the ability to quickly reprice the data and compute a new $/MLT is important. One approach is to use the price of a lumber grade such as 3 and Better Common to adjust the $/MLT by the ratio of new price to old price. As an example, we used a price of $283.65/MLT for 3 and Better Common (table 8). If the price rose to $350.00/MLT, then the $/MLT for each diameter class would be adjusted by the ratio of 350.00/283.65, or 1.23. The one advantage of using this approach is that it is quick; however, it assumes other lumber values will change in the same proportion and direction, and this may or may not be true.

A more accurate method of repricing lumber value is to estimate a new $/MLT weighted by the percentage of lumber volume in each lumber-grade group for each diameter class. As an example, consider a new set of lumber prices:

Grade group	$/MLT
Moulding and Better	$593.64
Shops	278.86
3 and Better Common	410.02
4 Common	207.40
5 Common	112.30

The new $/MLT for 6-inch logs is computed as follows:

5 Common	0.08×112.30	=	$ 8.98
4 Common	0.07×207.40	=	14.52
3 and Better Common	0.80×410.02	=	328.02
Shops	0.06×278.86	=	16.73
Moulding and Better	0.00×593.64	=	0.00
			$368.25

where 0.08, 0.07, 0.80, 0.06, and 0.00 are the proportions of the lumber volume produced from a 6-inch log in each lumber grade group (table 7);
112.30, 207.40, 410.02, 278.86, and 593.64 are the new lumber prices for these respective lumber grades or grade groups; and
368.25 is the new $/MLT for 6-inch logs.

This procedure can be repeated for each diameter class to produce a new $/MLT curve.

The price for Shops ($278.86) in the above calculations represents an average price weighted by the percentage of the Shop volume in the various Shop grades. The percentages of Shop grades manufactured during this study were as follows:

Shop grade	Percent
Factory Select/3 Clear	0.3
1 Shop	10.9
2 Shop	44.7
3 Shop	41.7
Shop outs	2.4

These proportions were used to calculate a weighted average price for the lumber-grade group "Shops" by using the new prices of the various Shop grades.

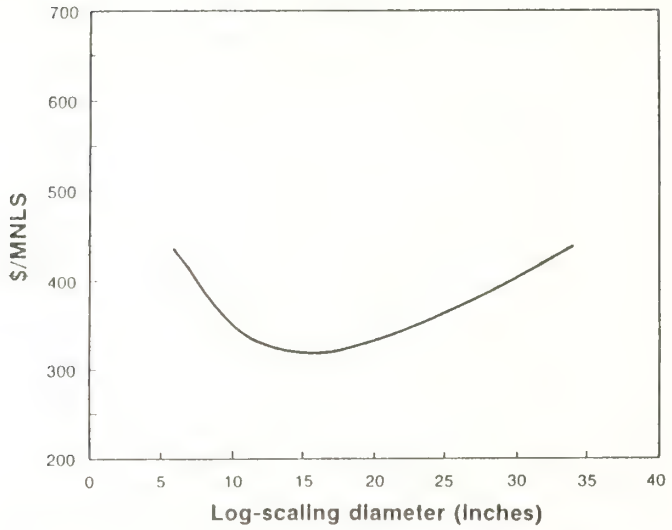


Figure 8—The relation of log value in dollars per thousand net log scale ($/MNLS) to scaling diameter.

$/MNLS—The $/MNLS was estimated for each diameter class by multiplying the board-foot recovery percent (table 3) by the average lumber value (table 9). The relation of $/MNLS to log diameter is shown in figure 8. The $/MNLS decreased for logs 6-14 inches in diameter because board-foot recovery percent decreased. Above 14 inches, the $/MNLS increased because of the recovery of high-valued lumber. Users can update the $/MNLS curve to future prices by updating the $/MLT and recomputing the diameter-class values.

$/CCF—The $/CCF was estimated for each diameter class by multiplying the cubic lumber recovery percent (table 5) by the board feet per cubic foot of lumber (BF/CF Lum, table 6) and the average lumber value ($/MLT, table 9). The values are shown plotted over scaling diameter in figure 9. The $/CCF increased with log size because both cubic recovery percent and the average lumber value increased over diameter. Users can update the $/CCF by updating the $/MLT and recomputing $/CCF.

Direct Product Estimators

Figure 10 shows the linear relation between the cubic volume output of incense-cedar products and the cubic product scale of the logs. Regression equations expressing these relations can be used to estimate the cubic product yield for logs with varying amounts of cubic product scale. Cubic yields of lumber volume estimated with the use of the regression equation can be converted to board feet by multiplying the cubic yields by the appropriate BF/CF Lum from table 6 (discussed earlier).

Log-Scale Conversion Factors

Log-scale conversion factors (BF/CF Log) enable users to convert Scribner log volumes to estimates of cubic-foot volumes. Conversion factors have been developed for several timber species (Cahill 1985, Hartman and others 1975); none are applicable to incense-cedar because of the type and extent of defect and the unusual taper of this species.

Computed values of BF/CF Log for gross and net scale were regressed over log diameter (fig. 11). The trend of increasing BF/CF Log with increasing diameter reflects the low estimates of Scribner board-foot volumes in smaller logs. The BF/CF Log based on net scales were consistently less than those for gross scales because, for a given defect, Scribner scaling rules dictate a greater proportion of log volume be deducted than is dictated by the cubic rules (see table 2). The BF/CF Log for gross and net scales are presented by 2-inch diameter classes in table 11.

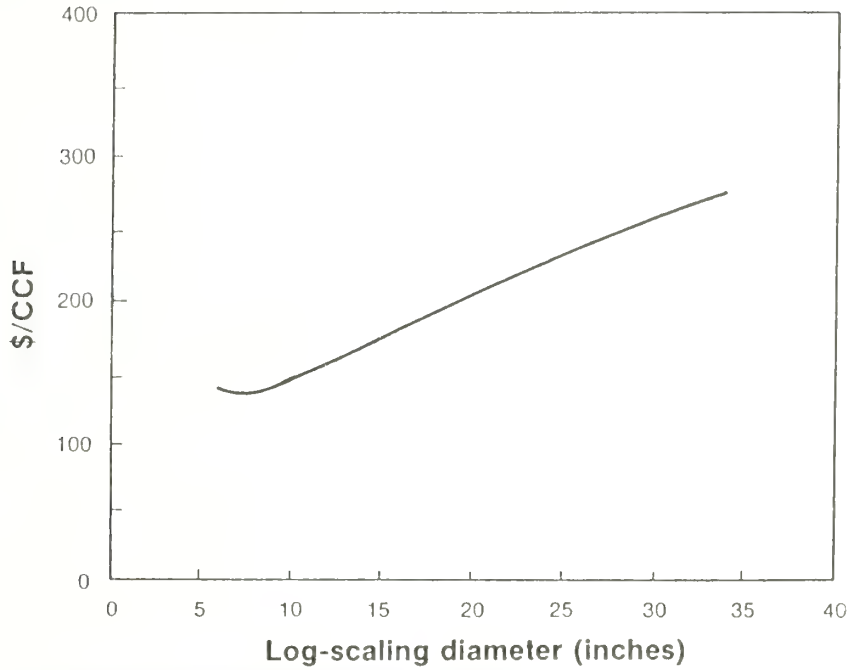


Figure 9—The relation of log value ($/CCF) in dollars per hundred cubic feet of cubic product scale to scaling diameter.

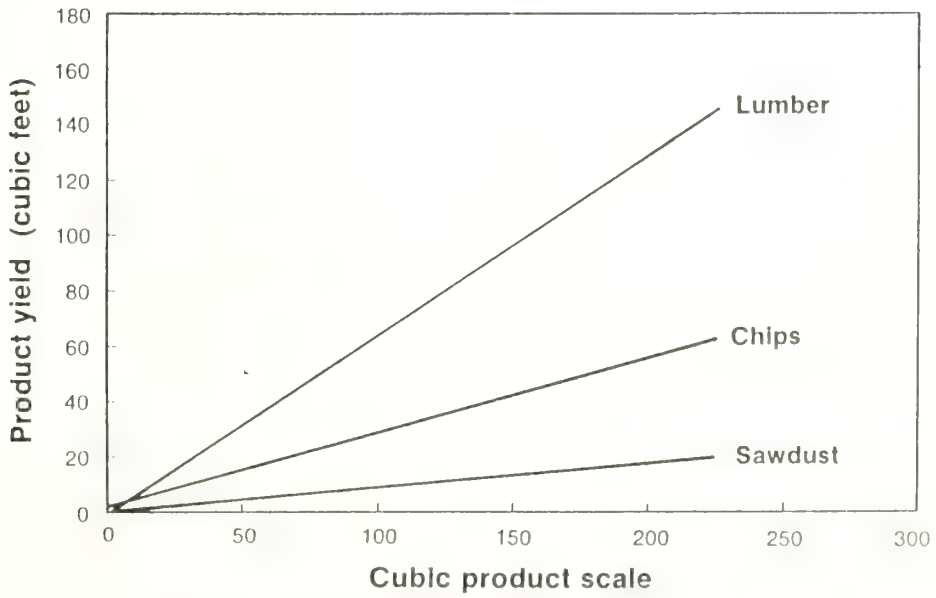


Figure 10—The relation of yield in cubic feet of rough green lumber, chips, and sawdust to cubic product scale. Regression equations are shown in appendix 3.

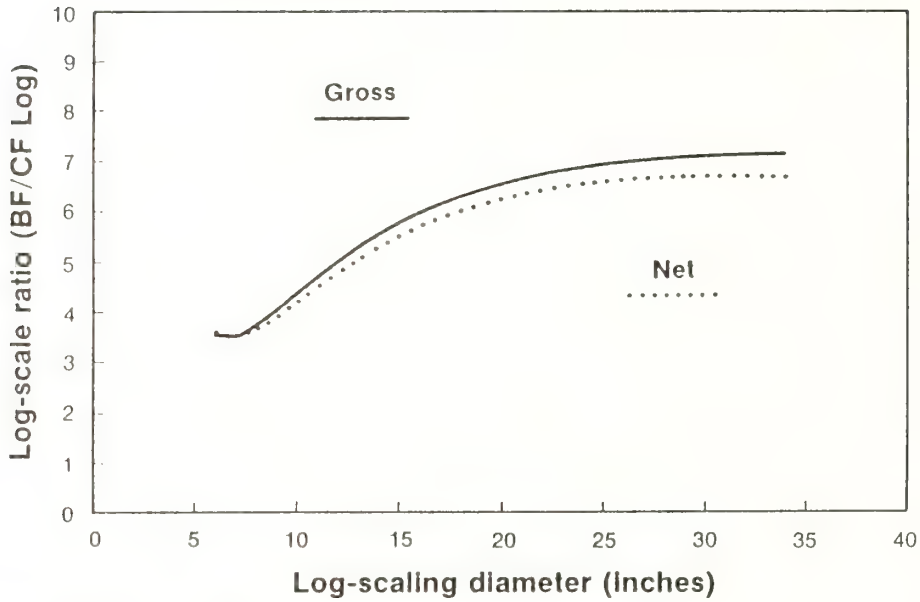


Figure 11—The relation of Scribner to cubic log-scale ratios to log diameter. Regression equations are shown in appendix 3.

Table 11—The ratio of Scribner board-foot scale to cubic-foot scale, by scaling diameter with 95-percent confidence interval (CI)

Scaling diameter	Gross BF/CF Log[a]	CI[b]	Net BF/CF Log[a]	CI[b]
Inches	----------Board feet per cubic foot---------			
6	3.55	0.25	3.59	0.38
8	3.74	.14	3.64	.22
10	4.39	.13	4.22	.20
12	5.03	.11	4.80	.17
14	5.56	.10	5.29	.15
16	5.98	.10	5.68	.16
18	6.31	.11	5.99	.17
20	6.56	.11	6.22	.17
22	6.76	.11	6.39	.17
24	6.90	.11	6.52	.17
26	7.01	.13	6.60	.20
28	7.08	.16	6.66	.25
30	7.12	.21	6.68	.32
32	7.14	.26	6.69	.40
34	7.13	.32	6.67	.49

[a]Regression equations listed in appendix 3.

[b]CI is the half-width of 95-percent confidence limit for the expected mean value of the dependent variables, BF/CF Log gross and BF/CF Log net.

Metric Equivalents

1 inch = 2.54 centimeters

1 foot = 0.3048 meter

1 cubic foot = 0.02832 cubic meter

1 pound = 453.6 grams

1 ton = 0.907185 metric ton

Literature Cited

Bruce, David. 1982. Butt log volume estimators. Forest Science. 28(3):489-503.

Cahill, James M. 1984. Log scale conversion factors. In: Snellgrove, Thomas A.; Fahey Thomas D.; Bryant, Ben S., tech. eds. User's guide for cubic measurement. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest And Range Experiment Station; Seattle, WA: University of Washington; College of Forest Resources; chapter 10.

Cahill, James M.; Pong, W.Y.; Weyermann, D.L. 1987. Pecky rot in incense-cedar: evaluation of five scaling methods. Res. Note PNW-RN-457. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 10 p.

Fahey, Thomas D. 1983. Product recovery from hemlock "pulpwood" from Alaska. Res. Pap. PNW-303. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 21 p.

Fahey, Thomas D.; Snellgrove, Thomas A. 1982. Measuring improvements in lumber recovery. Forest Industries. 109(13): 32-34.

Fahey, Thomas D.; Woodfin, Richard O., Jr. 1976. The cubics are coming: predicting product recovery from cubic volume. Journal of Forestry. 76(11): 739-743.

Hartman, David A.; Atkinson, William A.; Bryant, Ben S.; Woodfin, Richard O. 1975. Conversion factors for the Pacific Northwest forest industry. Seattle, WA: Institute of Forest Products, College of Forest Resources, University of Washington. 112 p.

Snellgrove, Thomas A.; Cahill, James M. 1980. Dead western white pine: characteristics, product recovery, and problems associated with utilization. Res. Pap. PNW-270. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 63 p.

U.S. Department of Agriculture, Forest Service. 1973a. National forest log scaling handbook. For. Serv. Handb. 2409.11, Amend. 4. Washington, DC. 184 p.

U.S. Department of Agriculture, Forest Service. 1973b. The outlook for timber in the United States. For. Resour. Rep. FRR-20. Washington, DC. 367 p.

Wise, H.F.; May, R.H. 1958. Lumber grade recovery from old-growth white fir on the Sequoia National Forest, California. Berkeley, CA: U.S. Department of Agriculture, Forest Service, California Region and California Forest and Range Experiment Station. 11 p.

Western Wood Products Association. 1981. Western lumber grading rules. Portland, OR. 222 p.

Appendix 1

Incense-cedar lumber-recovery and log-scale data available from PNW. Recovery is based on the woods-length log. Two records are available for each log.

First record (card type = 1)—

Information	Columns
Card type (1)	1 - 1
Tree/log number	2 - 5
Scribner log length	9 - 10
Large-end diameter	14 - 15
Small-end scaling diameter	19 - 20
Scribner gross board-foot scale	21 - 25
Scribner net 1-3/4-board-foot scale[1]	26 - 30
Scribner net 4-1/2-board-foot scale[2]	31 - 35
Board-foot lumber tally with cull boards	36 - 40
Board-foot lumber tally without cull boards	41 - 45
Gross cubic scale[3]	46 - 51
Product cubic scale[4]	52 - 57
Surface dry cubic-foot lumber tally	58 - 64
Sawdust volume in cubic feet	65 - 71
Rough green cubic-foot lumber tally	72 - 78

Second record (card type = 2)—

Information	Columns
Card type (2)	1 - 1
Tree/log number	2 - 5
Percent recovery in:	
Moulding	6 - 10
Factory Selects	11 - 15
1 Shop	16 - 20
2 Shop	21 - 25
3 Shop	26 - 30
Shop Outs	31 - 35
1 Common	36 - 40
2 Common	41 - 45
3 Common	46 - 50
4 Common	51 - 55
5 Common	56 - 60

[1] The rules for scaling pecky rot were modified in this study. Pockets of rot were squared out and deducted only if they were less than 1-3/4 inches apart; all other pockets were ignored

[2] The rules for scaling pecky rot were modified in this study. Pockets of rot were squared out and deducted only if they were less than 4-1/2 inches apart; all other pockets were ignored.

[3] Gross cubic log volumes were calculated using two formulas: Bruce's formula for the butt segment and Smalian's formula for all other logs.

[4] Cubic product scale is gross cubic scale reduced for all defects expected to reduce the yield of primary and secondary products.

Appendix 2

Definitions and Formulas for Measures of Product Recovery

Board-foot recovery percent—The board-foot lumber tally divided by net Scribner log scale:

$$\frac{\text{Board-foot lumber tally}}{\text{Scribner net log scale}} \times 100 .$$

Cubic-lumber recovery percent—The cubic-foot volume of rough green lumber divided by the cubic product scale:

$$\frac{\text{Cubic-foot lumber volume}}{\text{Cubic product scale}} \times 100 .$$

Cubic-foot lumber volume was calculated by applying measurements of rough green lumber to the shipping tally.

Cubic sawdust-recovery percent—The cubic-foot volume of sawdust divided by the cubic product scale:

$$\frac{\text{Cubic-foot volume of sawdust}}{\text{Cubic product scale}} \times 100 .$$

Sawdust volume is estimated using the surface area of the lumber and an average saw kerf.

Cubic chip-recovery percent—The cubic volume of chippable log residue divided by the cubic product scale:

$$\frac{\text{Cubic-foot volume of chippable residue}}{\text{Cubic product scale}} \times 100 .$$

Chippable residue is estimated by subtracting the cubic volume of rough green lumber plus the cubic volume of sawdust from the cubic product scale.

Board foot per cubic foot of lumber (BF/CF Lum)—The nominal board-foot lumber tally divided by the rough green cubic-foot volume of lumber:

$$\text{BF/CF Lum} = \frac{\text{board-foot lumber tally}}{\text{cubic-foot volume of rough green lumber}} .$$

Percent lumber-grade recovery—The proportion of total board-foot lumber volume in each lumber grade group:

$$\frac{\text{Board-foot lumber volume for any grade group}}{\text{Total board-foot lumber volume}} \times 100 .$$

Dollars per thousand board-foot lumber tally—The total value of the lumber manufactured divided by the lumber tally:

$$\$/MLT = \frac{\text{lumber value}}{\text{board-foot lumber tally}} .$$

Dollars per thousand net Scribner log scale—Computed using the previously defined recovery ratios of board-foot recovery percent and $/MLT:

$$\$/MNLS = \text{board-foot recovery percent} \times \$/MLT.$$

Dollars per hundred cubic feet of cubic product scale—Computed using the previously defined recovery ratios BF/CF Lum, cubic recovery percent of rough green lumber, and $/MLT:

$$\$/CCF = \text{BF/CF Lum} \times \text{cubic recovery percent of rough green lumber} \times \text{BF/CF Lum} .$$

Board feet of log scale per cubic foot of log scale—The Scribner log-scale volume divided by the cubic log-scale volume. Two ratios are calculated—one for gross scale and one for net scale:

$$\text{BF/CF Log gross} = \frac{\text{gross Scribner scale}}{\text{gross cubic scale}} ; \text{ and}$$

$$\text{BF/CF Log net} = \frac{\text{net Scribner scale}}{\text{cubic product scale}} .$$

Appendix 3

List of regression equations used to generate figures and tables for incense-cedar. Formulas used to calculate dependent variables are shown in appendix 2.

Dependent variable	Regression model	R^2	SE	Table	Figure
	Lumber recovery equations				
Board-foot recovery percent	89.1+476.7(1/D)	0.18	40.26	3	2
Board-foot recovery percent	$77.0+523.7(1/D)+0.034(DEF)^2$	.38	35.53	4	
Cubic lumber recovery percent	$140.9-1.46(D)-1089(1/D)+3581(1/D)^2$	.29	10.72	5	4
Cubic lumber plus sawdust percent	$154.7-1.53(D)-1171(1/D)+3874(1/D)^2$	.28	12.03	5	4
BF/CF Lum	10.34+0.915(1/D)	.18	.08	6	
	Lumber grade recovery equations[a]				
Percent 5 Common	8.0 (no relation with diameter)			7	5
Percent 4 + 5 Common	52.9-0.8(D)-201.2(1/D)	.03	22.10	7	5
Percent all Commons (5+4+3+2+1)	$72.3+7.36(D)-0.876(D)^2+0.106(D)^{2.5}$	.74	13.19	7	5
Percent all Commons plus Shops	$96.85+0.8(D)-0.049(D)^2$	.49	7.27	7	5
Percent Moulding	100 percent – all Commons plus Shops			7	5
Percent 5 Common	4.08+0.48(DEF)	.19	13.35		6
	Lumber value equations[b]				
$/MLT	$-108.0+13.06(D)+3260.8(1/D)-9245.7(1/D)^2$	.32	56.19	9	7
$/MLT	$-100.3+13.34(D)+3247.9(1/D)-9333.2(1/D)^2-1.19(DEF)$	.38	53.78	10	
	Direct product equations				
Lumber yield in cubic feet	-0.88+0.65(cubic product scale)	.96	7.23		10
Chip yield in cubic feet	1.66+0.27(cubic product scale)	.75	8.34		10
Sawdust yield in cubic feet	-0.09+0.09(cubic product scale)	.97	.83		10
	Log-scale conversion factors				
BF/CF Log gross	$13.19-0.807(D)-116.15(1/D)+368.77(1/D)^2$	.76	.71	11	
BF/CF Log net	$12.83-0.092(D)-114.0(1/D)+371.1(1/D)^2$	.52	1.10	11	

D = scaling diameter in inches,
DEF = percent of Scribner scaling defect,
R^2 = coefficient of determination, and
SE = standard error of the regression.

[a]Grade-recovery equations are cumulative. To estimate the percent in any one grade group, the percent of the previous grade group must be subtracted. For example, to estimate the percent of 4 Common lumber, the percentage of 5 Common is subtracted from the estimate for 4 + 5 Common

[b]$/MLT based on 1985 prices.

GPO 593-223/80100

Pong W.Y.; Cahill, James M. 1988. Lumber recovery from incense-cedar in central California. Res Pap. PNW-RP-393. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 22 p

A sample of 130 incense-cedar (*Libocedrus decurrens* Torr.) trees was selected from the Eldorado National Forest in California. The trees were felled and bucked into 403 woods-length logs and processed through a sawmill cutting Shop and Common grades of lumber. Recovery estimates are shown for woods-length logs based on Scribner board-foot scale and cubic-foot scale. Analysis showed that board-foot recovery ranged from 169 percent for 6-inch logs to 103 percent for 34-inch logs. Cubic-volume recovery of rough green lumber increased from 50 percent to 62 percent for the same range of diameters. Yields of higher quality lumber (Shops and Moulding) increased as log diameter increased. Percentage of Scribner scaled defect was found to be correlated with several measures of product recovery.

Keywords: Lumber recovery, lumber value, incense-cedar, log scale, California.

The **Forest Service** of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives—as directed by Congress—to provide increasingly greater service to a growing Nation.

The U.S. Department of Agriculture is an Equal Opportunity Employer. Applicants for all Department programs will be given equal consideration without regard to age, race, color, sex, religion, or national origin.

Pacific Northwest Research Station
319 S.W. Pine St.
P.O. Box 3890
Portland, Oregon 97208

April 1988

U.S. Department of Agriculture
Pacific Northwest Research Station
319 S.W. Pine Street
P.O. Box 3890
Portland, Oregon 97208

Official Business
Penalty for Private Use, $300

BULK RATE
POSTAGE +
FEES PAID
USDA-FS
PERMIT No. G-40

do NOT detach label

United States
Department of
Agriculture

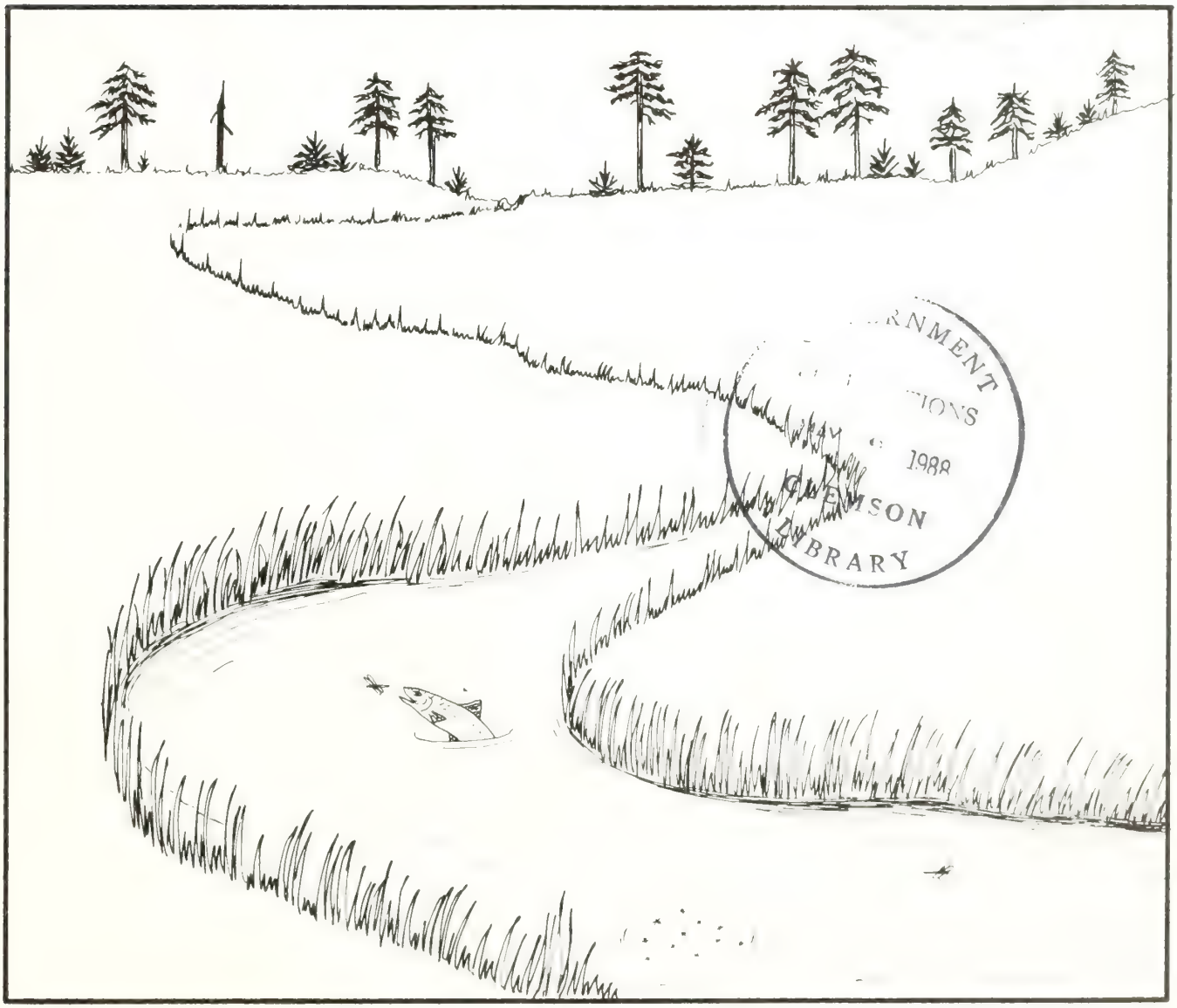
Forest Service

Pacific Northwest
Research Station

Research Paper
PNW-RP-394

Invertebrates of Meadow Creek, Union County, Oregon, and Their Use as Food by Trout

Carl E. McLemore and William R. Meehan



RNMENT
IONS
1988
SON
BRARY

Authors

CARL E. McLEMORE is a biological technician (fisheries), Forestry Sciences Laboratory, 3200 Jefferson Way, Corvallis, Oregon 97331.

WILLIAM R. MEEHAN is a research fisheries biologist, Forestry Sciences Laboratory, P. O. Box 20909, Juneau, Alaska 99802.

Abstract

McLemore, Carl E.; Meehan, William R. 1988. Invertebrates of Meadow Creek, Union County, Oregon, and their use as food by trout. Res. Pap. PNW-RP-394. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 13 p.

From 1976 to 1980, invertebrates were collected three times each year from several reaches of Meadow Creek in eastern Oregon. Five sampling methods were used: benthos, drift, sticky traps, water traps, and fish stomachs. A total of 372 taxa were identified, of which 239 were used as food by rainbow trout (steelhead; *Salmo gairdneri* Richardson). Of the taxa found in trout stomachs, 71 (29.5 percent) were terrestrial.

Keywords: Invertebrates, aquatic life, salmonids.

Contents

1 **Introduction**

1 **Study Area**

2 **Materials and Methods**

2 Sample Types

3 Sampling Schedule

3 Identification of Organisms

3 **Results and Discussion**

12 **Literature Cited**

Introduction

From 1976 to 1980, we sampled stream invertebrates of Meadow Creek, Union County, Oregon. The objective of this paper is to list the taxa collected during spring, summer, and fall by five sampling methods. This information was obtained as part of a broader study of the effects of livestock grazing on fish habitat, the results of which will be reported later.

Study Area

The stream selected for study was Meadow Creek, a fourth-order tributary of the Grande Ronde River in the Blue Mountains of northeastern Oregon, about 48 km southwest of LaGrande (fig. 1). The study sections of Meadow Creek are located on the Starkey Experimental Forest and Range. The stream maintains populations of resident (rainbow) and anadromous (steelhead) trout (*Salmo gairdneri* Richardson). Minimum streamflow, maintained mainly by springs, fluctuates with summer storms (Bryant and Skovlin 1982). Stream temperatures range from 0 °C in winter, when surface water is frozen and deep pools remain unfrozen, to about 26.7 °C in midsummer. The stream is about one-fourth shaded (Bryant and Skovlin 1982) by ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and lodgepole pine (*Pinus contorta* Dougl. ex Loud.), and to a lesser extent, by mountain alder (*Alnus tenuifolia* Nutt.) and willow (*Salix* spp.).

Ten study sections were established on the stream (fig. 1). The physical features of all sections were similar. The streambed at sampling sites varied from sand (1.5 mm in diameter) to large cobbles (127.0 to 254.0 mm in diameter).

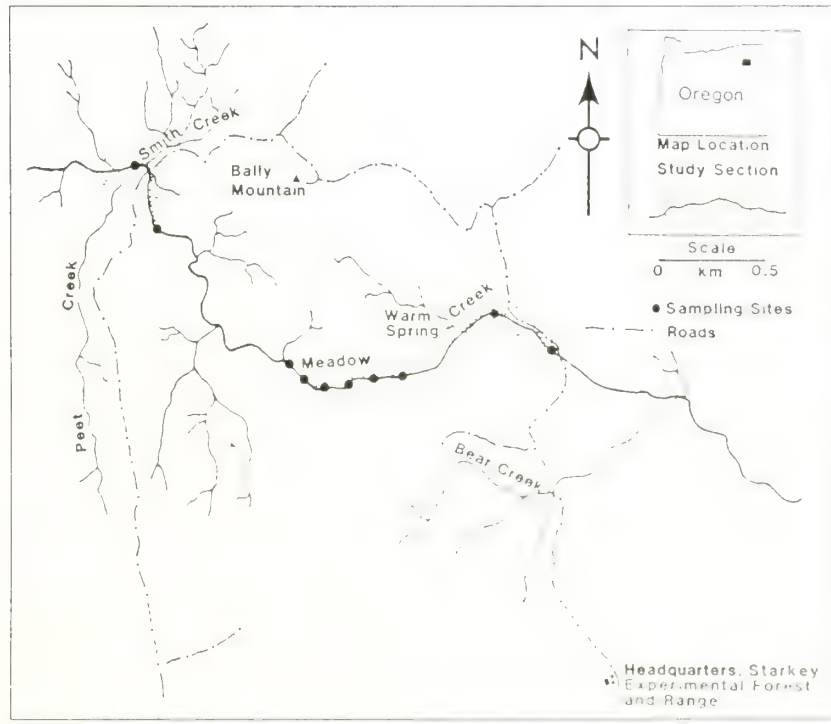


Figure 1—Locations of sampling sites.

Materials and Methods

Sample Types

Benthos.—Benthic samples were collected with a modified Hess sampler[1] covering a surface area of 0.09 m^2. Two samples were collected from each study section and preserved in formal alcohol (half 70 percent ethanol and half 10 percent formalin). In the laboratory, invertebrate organisms were sorted from the samples, counted, and identified to the lowest feasible taxon (generally to family, and to genus or species where practicable); the entire sample was then freeze dried and weighed on an analytical balance to the nearest one-tenth milligram.

Drift.—Aquatic drift was sampled in each study section with a 280-micrometer-mesh Nitex drift net, 76 cm long. Drift net openings were 0.46 by 0.31 m. During each sampling period, drift was sampled for 24 h. Samples were processed in the field and in the laboratory as described above.

Sticky traps and water traps.—Terrestrial insects and adult aquatic insects that drop into the stream and become part of the drift and potential fish food supply were collected during each sampling period by sticky traps and water traps. A pair (one of each type) was placed at each of two sites within each study section.

A sticky trap consisted of a 0.31-m^2 piece of 6.35-mm plywood (painted white) covered with a piece of 6-mil clear polyethylene film. This 0.31-m^2 surface was then sprayed with "Tree Tanglefoot," a sticky substance used to trap crawling insects on trees. The board was then taped to a 0.36-m by 0.36-m by 5.1-cm-thick styrofoam float. When the trap was removed from the stream at the end of a sampling period, the plastic film was cut off at the edges of the board so that a 0.31-m^2 collection surface was retained. Butcher paper was placed over the sticky side to prevent crushing or mold damage to the specimens, and the film and butcher paper "sandwich" was transported to the laboratory. In the laboratory, the butcher paper was removed from the film, which was then cut into 2.54-cm strips for viewing under a microscope. Insects were counted and identified to the lowest possible taxon, usually family.

A water trap was made from a 0.33- by 0.28-m plastic dishpan, 0.13 m deep, surrounded by a 0.61- by 0.61-m ring of 5.1-cm-thick styrofoam that supported and floated the pan. The pan was filled to about half its depth with water, to which 28.4 g of formalin and 28.4 g of a surfactant (Ortho RX-77 Spreader) were added. The surfactant eliminated water surface tension and allowed insects to settle to the bottom of the pan. A small hole was bored into a lower corner of the pan and fitted with a rubber stopper to facilitate removal of the contents. When a water trap was removed from the stream at the end of a sampling period, the corner plug was removed and the contents of the pan were strained through a 0.5-mm-mesh screen. The material remaining on the screen was washed off into a jar with formal alcohol and then processed as described for benthic and drift samples.

---

[1] The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture of any product or service to the exclusion of others that may be suitable

Fish stomachs.—During each sampling trip, 10 steelhead (rainbow) trout were captured by electrofishing in each study section. Fish were anesthetized with Tricaine Methanesulfonate, MS-222, and then were measured and weighed. Stomachs were flushed by use of the technique described by Meehan and Miller (1978). Samples were treated and analyzed in the field and laboratory in a manner similar to that for benthic, drift, and water trap samples. Fish from 50- to 150-mm fork length were used when possible because complete flushing of larger fish was difficult and error was more likely in feeding habits for different size classes of fish.

Sampling Schedule

Samples were collected three times each year (1976-80) in spring (mid-May to late May), summer (late July to early August), and fall (late October to early November). Sampling periods varied from 3 to 7 days; 5 days was the usual duration. Sticky traps and water traps were set out in each study section at the beginning of a sampling period and removed at the end of the period. As each study section was sampled, a drift net was set out for 24 h, during which time the benthic and fish stomach samples for that section were collected.

Identification of Organisms

Several publications were used in identifying the organisms collected. Invertebrates, other than insects, were identified through descriptions in Ward and Whipple (1959), Miller (1960), and Pennak (1978). Aquatic insects were identified by means of taxonomic keys in Hatch (1953, 1957, 1961, 1965, 1971), Usinger (1956), Jensen (1966), Cole (1969), Anderson (1976), Edmunds and others (1976), Baumann and others (1977), Wiggins (1977), and Merritt and Cummins (1978). Terrestrial insects were identified primarily from Borror and others (1976) and Richards and Davies (1977).

Results and Discussion

Invertebrates were listed as aquatic or terrestrial, based on the organism's habitat for most of its life (table 1).

Three taxonomic groups (10 individual organisms) were collected only on sticky traps: Pseudoscorpionida (scorpionlike spider), Cyclorrhapha (suborder of Diptera), and Cydnidae (gall wasps). The relative abundance of individual taxa collected on sticky traps was less than one-third that collected by the other trapping methods:

Method	Taxon
Benthos	210
Drift	248
Sticky traps	69
Water traps	209
Stomachs	239

The terrestrial contribution to the sticky trap sampling was 33 taxa or 47.8 percent. Some problems inherent in sticky trap sampling are: less precise identification of taxa, decomposition, predation, variation in application of Tanglefoot, and the escape of large organisms from the Tanglefoot.

In the benthic samples, 30 taxa (14.5 percent) were terrestrial. Terrestrial taxa drop into streams during flight, or they drop from overhanging vegetation and are carried in stream currents until they lodge in the substrate.

In drift samples, 66 taxa (25.6 percent) were terrestrial. This percentage compares closely with the 29.5 percent found in stomach samples.

Of the taxa collected in water traps, 88 (41.6 percent) were terrestrial. Water trap and sticky trap samples were expected to contain a higher percentage of terrestrial taxa than were samples collected by the other methods, and the percentage of composition of invertebrates collected by these two types of trap is similar.

The most abundant taxon collected during the study was the family Chironomidae (32,484 individuals). Chironomids were found in 713 of the 930 fish stomachs sampled. The second most numerous taxon was the genus *Lepidostoma* (31,765 individuals); 484 stomachs (52 percent) contained this genus.

Examination of stomach contents presents many problems, not the least of which is the identification of the prey that have been eaten. *Baetis hageni* (*parvus*) Eaton is an excellent example. The data show that 3,306 *B. hageni* were collected during the study, but this species was found only in benthic and drift samples. The only baetids found in stomach samples that could be identified to species were *B. bicaudatus* and *B. tricaudatus*. If *B. hageni* were present in stomach samples, they were identified only to the genus, family, or order level. Even a skilled entomologist is at a disadvantage if only mangled pieces of organisms remain to study without well-preserved general collections from the habitat where the fish were feeding.[2]

Stomach samples of juvenile salmonids show that the fish consume a wide variety of organisms (Siebert and Kask 1978). We collected 372 taxa by the several sampling methods; trout stomachs contained 239 (64.2 percent) of these taxa. The availability of a given prey is not determined simply by its abundance, but also by the predator's feeding strategy and the behavior and morphology of the prey (Chess 1978).

Terrestrial, as well as aquatic, ecosystems are sources of invertebrate food for fish. Streambanks and the entire riparian zone are particularly important. The terrestrial component of the diet of trout in our study was 71 taxa (29.5 percent), which demonstrates the value of riparian habitat.

---

[2] Personal communication, Kenneth W. Cummins, Appalachian Environmental Laboratory for Environmental and Estuarine Studies, University of Maryland, Frostburg State College Campus, Frostburg, MD 21532.

Table 1—Invertebrates collected from Meadow Creek, Union County, Oregon, 1976-80

Taxon	Number	Sample type[1]	Habitat type[2]	Season[3]	Life stage[4]
Turbellaria					
Tricladida					
Planariidae	34	1	A	1,3	A
Nematoda	454	1,2,4,5	A	1,2,3	LA
Oligochaeta	1,992	1,2,4,5	A	1,2,3	LA
Hirudinea	12	1,5	A	1,2,3	A
Gastropoda	10	1,5	A	1,3	A
Basommatophora					
Physidae					
Physa spp.	231	1,2,4,5	A	1,2,3	LA
Planorbidae	1	1	A	3	A
Ancylidae	43	1	A	1,2,3	A
Lancidae					
Lanx spp.	6	1	A	3	A
Pelecypoda	2	1,5	A	3	A
Sphaeriidae	30	1	A	1,2,3	A
Unionidae	3	1	A	2,3	A
Crustacea					
Decapoda					
Astacidae	8	1,5	A	1,2,3	A
Pacifastacus (Astacus) sp.	1	1	A	3	A
P. klamathensis (Stimpson)	1	1	A	3	A
P. trowbridgi (Stimpson)	28	1,2	A	1,2,3	A
Isopoda	1	2	T	1	A
Ostracoda	15	1,2,4	T	2,3	A
Copepoda	4	1,2,5	A	2,3	A
Arachnida					
Araneae	2,440	1, 2, 3, 4, 5	T	1, 2, 3	A
Acarina	1,235	1, 2, 4, 5	T	1, 2, 3	A
Pseudoscorpionida	2	3	T	1	A
Opiliones	9	3, 4	T	1, 2, 3	A
Insecta	4	2, 4, 5	U	1, 2, 3	LPA
Dermaptera	2	4, 5	T	3	A
Forficulidae	2	4	T	2, 3	A
Collembola	70	2, 3, 4, 5	A	1, 2, 3	A
Entomobryidae	62	1, 2, 5	A	1, 2, 3	LA
Sminthuridae	8	2, 4	A	1, 2, 3	A
Poduridae	390	1, 2, 3, 4, 5	A	1, 2, 3	A
Isotomidae	181	1, 2, 3, 4, 5	A	1, 2, 3	A
Ephemeroptera	1,090	2, 3, 4, 5	A	1, 2, 3	LA
Siphlonuridae	1	4	A	3	A
Siphlonurus spp.	9	2	A	2, 3	L
Ameletus spp.	600	1, 2, 4, 5	A	1, 2, 3	LA
Tricorythidae					
Tricorythodes spp.	1,084	1, 2, 4, 5	A	1, 2, 3	LA
Baetidae	787	1, 2, 4, 5	A	1, 2, 3	LA
Baetis spp.	1,043	1, 2, 4, 5	A	1, 2, 3	LA
B. bicaudatus Dodds	21	2, 4, 5	A	1, 2, 3	LA
B. hageni (parvus) Eaton	3,306	1, 2	A	1, 2, 3	L
B. tricaudatus Dodds	3,098	1, 2, 4, 5	A	1, 2, 3	L
Centroptilum spp.	2,045	1, 2, 4, 5	A	1, 2, 3	LA
Pseudocloeon sp.	1,559	1, 2, 4, 5	A	1, 2, 3	LA
Heptageniidae	424	1, 2, 3, 4, 5	A	1, 2, 3	LA
Epeorus spp.	378	1, 2, 4, 5	A	1, 2, 3	L
E. longimanus Eaton	1,386	1, 2, 5	A	1, 2, 3	LA
Cinygmula spp.	1,039	1, 2, 4, 5	A	1, 2, 3	L
Cinygma spp.	7	1, 4, 5	A	1, 2, 3	L
Heptagenia sp.	119	5	A	2	L

Table 1—Invertebrates collected from Meadow Creek, Union County, Oregon, 1976-80 (continued)

Taxon	Number	Sample type[1]	Habitat type[2]	Season[3]	Life stage[4]
H. criddlei McDunnough	935	1, 2, 4, 5	A	1, 2, 3	LA
Rhithrogena spp.	8	1, 2	A	3	L
R. hageni Eaton	29	1	A	3	L
R. robusta Dodds	35	1, 2	A	3	L
Leptophlebiidae	7	4	A	1, 2, 3	A
Paraleptophlebia spp.	705	1, 2, 3, 4, 5	A	1, 2, 3	LA
P. bicornuta McDunnough	568	1, 2, 4, 5	A	1, 2, 3	L
P. debilis (Walker)	13	1, 2, 5	A	1, 3	L
P. temporalis McDunnough	3,222	1, 2, 5	A	1, 2, 3	LA
Ephemerellidae	3	4	A	3	A
Ephemerella spp.	1,498	1, 2, 3, 4, 5	A	1, 2, 3	LA
E. aurivillii Bengtsson	58	5	A	1, 2, 3	L
E. dodd Needham	104	1, 2, 5	A	1, 3	L
E. flavilinea McDunnough	52	1, 2	A	1, 3	L
E. grandis Eaton	54	1, 2, 5	A	1, 3	L
E. infrequens McDunnough	4,961	1, 2, 4, 5	A	1, 2, 3	L
E. spinifera Needham	6	1, 2	A	1, 2	L
E. tibialis McDunnough	283	1, 2, 5	A	1, 2, 3	L
E. (Drunella) sp. Needham, Edmonds	8	1, 2, 5	A	1	L
E. hecuba Eaton	12	1, 5	A	2	L
E. margarita Needham	539	1, 2	A	1, 2, 3	L
E. (Serratella) spp. Edmunds	41	5	A	1, 2, 3	L
E. (Ephemerella) spp. Walsh	20	5	A	1, 2, 3	L
Odonata	19	1, 3	A	1, 2, 3	LA
Gomphidae	63	1, 2	A	1, 2, 3	LA
Aeshnidae	1	5	A	2	L
Orthoptera	26	2, 3, 4, 5	T	1, 2, 3	LA
Gryllacrididae	1	4	T	3	A
Acrididae	12	1, 2, 4, 5	T	1, 2, 3	LA
Plecoptera	252	1, 2, 3, 4, 5	A	1, 2, 3	LA
Pteronarcidae					
Pteronarcella sp.	1	U	A	U	L
Pteronarcys spp.	5	1, 5	A	1, 2, 3	L
P. princeps Banks	3	1, 4	A	1, 2, 3	LA
P. californica Newport	15	1, 2	A	1, 2, 3	L
Taeniopterygidae					
Taenionema sp.	5	2, 4, 5	A	1	A
Nemouridae	190	2, 4, 5	A	1, 3	LA
Soyedina spp.	1	4	A	1	A
Visoka sp.	1	2	A	3	L
Nemoura spp.	193	1, 2, 4, 5	A	1	LA
N. (Nemoura) sp.	11	2, 4, 5	A	1	LA
Zapada spp.	153	1, 2, 4, 5	A	1, 2	LA
Zapada cinctipes Banks	1,053	1, 2, 4, 5	A	1, 2, 3	LA
Malenka spp.	3	5	A	1, 3	L
Podmosta spp.	1,168	1, 2, 4, 5	A	1, 2, 3	LA
Amphinemoura sp.	2	5	A	1, 2	L
Leuctridae	7	1, 4, 5	A	1, 2	LA
Leuctra sp.	1	4	A	1	A
Despaxia augusta Banks	5	1	A	1, 3	L
Paraleuctra spp.	25	1, 2, 5	A	1, 2, 3	LA
Megaleuctra sp.	1	5	A	1	A
Capniidae	528	1, 2, 4, 5	A	1, 2, 3	LA
Eucapnopsis sp.	73	2, 4, 5	A	1	LA
Capnia sp.	1	4	A	1	A
Capnia spp.(complex)	322	1, 2	A	1, 3	L
Utacapnia sp.	1	4	A	1	A
Perlidae	3,752	1, 2, 5	A	1, 2, 3	LA
Acroneuria spp.	6	4, 5	A	1, 3	L
Calineuria californica (Banks)	3,902	1, 2, 5	A	1, 2, 3	L
Perlodidae	178	1, 2, 4, 5	A	1, 2, 3	LA
Isoperla spp.	56	1, 2, 3, 4, 5	A	1, 2, 3	LA

Table 1—Invertebrates collected from Meadow Creek, Union County, Oregon, 1976-80 (continued)

Taxon	Number	Sample type[1]	Habitat type[2]	Season[3]	Life stage[4]
I. fusca (Needham and Claassen)	1	1	A	1	L
I. marmorata (Needham and Claassen)	1	4	A	1	A
Perlinodes aurea Smith	583	1, 2, 4, 5	A	1, 2, 3	LA
Skwala spp.	[illegible]	1, 2, 4	A	1, 2, 3	LA
Cultus sp.	2	2	A	3	L
Chloroperlidae	2,760	1, 2, 3, 4, 5	A	1, 2	LA
Sweltsa spp.	108	1, 2, 4, 5	A	1, 2	LA
S. coloradensis Banks	2	2	A	1	A
Psocoptera	67	2, 4, 5	T	1, 2, 3	LA
Mallophaga	1	4	T	1	A
Thysanoptera	72	1, 2, 4, 5	T	1, 2, 3	LA
Hemiptera	162	1, 2, 3, 4, 5	A	1, 2, 3	LA
Corixidae	248	1, 2, 3, 4, 5	A	1, 2, 3	LA
Graptocorixa spp.	14	2	A	3	A
Hesperocorixa sp.	2	2	A	1	A
Cydnidae	3	3	T	1	A
Scutelleridae	1	2	T	3	A
Gerridae	47	2, 3	A	1, 2, 3	LA
Gerris spp.	292	1, 2, 3, 4, 5	A	1, 2, 3	LA
Trepobates spp.	14	2, 4, 5	A	2, 3	A
Veliidae	1	4	A	2	A
Rhopalidae	3	2, 5	T	3	A
Saldidae	89	3, 4, 5	T	1, 2, 3	LA
Anthocoridae	3	2	T	2, 3	A
Miridae	26	1, 2, 4, 5	T	1, 2, 3	A
Nabidae	13	1, 2, 4, 5	T	1, 2, 3	A
Reduviidae	1	4	T	2	A
Lygaeidae	49	2, 4, 5	T	1, 2, 3	LA
Berytidae	1	5	T	2	A
Pentatomidae	4	2, 4, 5	T	2, 3	A
Homoptera	453	1, 2, 3, 4, 5	T	1, 2, 3	LPA
Membracidae	1	4	T	3	A
Cicadellidae	3,843	1, 2, 3, 4, 5	T	1, 2, 3	LA
Cercopidae	53	1, 2, 3, 4, 5	T	1, 2, 3	LA
Delphacidae	29	1, 2, 4, 5	T	1, 2, 3	LA
Psyllidae	81	1, 2, 3, 4, 5	T	1, 2, 3	LA
Aphididae	728	1, 2, 3, 4, 5	T	1, 2, 3	LA
Adelgidae	111	2, 4, 5	T	2, 3	LA
Eriosomatidae	6	4, 5	T	3	A
Coleoptera	197	1, 2, 3, 4, 5	A	1, 2, 3	LA
Lathridiidae	1	2	T	3	A
Carabidae	102	1, 2, 3, 4, 5	T	1, 2, 3	A
Haliplidae	8	1, 2, 3, 5	A	1, 2, 3	LA
Haliplus spp.	18	2, 4	A	2, 3	LA
Brychius spp.	78	1, 2, 5	A	1, 2, 3	LA
Polyphaga spp.	8	5	A	2	LA
Amphizoidae	12	1, 2	A	1, 2, 3	LA
Dytiscidae	26	1, 2, 3, 4, 5	A	1, 2, 3	LA
Deronectes sp.	2	1, 2	A	1, 3	A
Oreodytes spp.	5	3, 5	A	1, 2, 3	A
Bidessus spp.	12	2	A	3	A
Hydroporus spp.	13	2, 5	A	1, 2, 3	A
Dermestidae	2	1, 2	A	2, 3	A
Histeridae	2	5	A	3	A
Hydrophilidae	20	2, 4, 5	A	1, 2, 3	LA
Hydrochus sp.	1	4	A	2	A
Paracymus spp.	24	1, 2, 5	A	1, 2, 3	LA
Anacaena sp.	2	2	A	1, 3	A
Chaetarthria sp.	1	1	A	1	A
Laccobius sp.	1	2	A	3	A
Sphaeridium sp.	1	2	A	1	A
Berosus sp.	1	2	A	3	A

Table 1—Invertebrates collected from Meadow Creek, Union County, Oregon, 1976-80 (continued)

Taxon	Number	Sample type[1]	Habitat type[2]	Season[3]	Life stage[4]
Helophorus spp.	6	2, 3, 5	A	1, 2, 3	A
Hydrobius sp.	1	5	A	1	A
Hydraenidae					
Hydraena spp.	95	2, 4	A	1, 2, 3	A
Ochthebius sp.	10	2	A	1, 3	A
Scarabaeidae	19	2, 4, 5	T	1, 3	A
Ptiliidae	13	2, 4, 5	T	1, 2, 3	A
Chrysomelidae	98	1, 2, 4, 5	A	1, 2, 3	A
Staphylinidae	661	1, 2, 3, 4, 5	A	1, 2, 3	LA
Scydmaenidae	3	4, 5	T	3	A
Cantharidae	48	1, 2, 4, 5	T	1, 2, 3	LA
Curculionidae	28	1, 2, 4, 5	T	1, 2, 3	A
Scolytidae	37	2, 4, 5	T	1, 2, 3	A
Elateridae	13	2, 3, 5	T	1, 2, 3	A
Byrrhidae	12	4, 5	T	1, 2, 3	A
Buprestidae	1	4	T	2	A
Psephenidae	6	1, 2	A	1, 2	L
Elmidae	110	1, 2, 3, 4, 5	A	1, 2, 3	LA
Heterlimnius spp.	42	1, 2, 4, 5	A	2, 3	LA
H. koebelei Martin	208	1, 2, 5	A	1, 2	A
Optioservus spp.	2,436	1, 2, 4, 5	A	1, 2, 3	LA
O. divergens (Le Conte)	3	1	A	1, 3	A
Narpus spp.	21	1	A	1, 2, 3	L
N. angustus Casey	6	1, 2	A	1, 2, 3	A
Zaitzevia spp.	638	1, 2	A	1, 2, 3	L
Z. parvula (Horn)	326	1, 2, 4, 5	A	1, 2, 3	A
Microcylloepus pusillus Le Conte	7	1	A	2, 3	LA
Cleptelmis spp.	53	1, 2, 5	A	1, 2, 3	LA
C. ornata (Schaeffer)	47	1, 2, 5	A	1, 2, 3	A
C. addenda (Fall)	1	1	A	3	A
Ordobrevia sp.	450	1, 2, 5	A	1, 2, 3	LA
O. nubifera (Fall)	83	1, 2	A	1, 2, 3	LA
Derodontidae	1	U	T	U	A
Cryptophagidae	1	2	T	1	A
Rhizophagidae	3	5	T	1, 3	A
Nitidulidae	5	2, 4, 5	T	1, 2, 3	A
Cucujidae	1	4	T	2	A
Coccinellidae	9	2, 3, 4, 5	T	1, 2, 3	A
Cerambycidae	6	4, 5	T	1, 2	A
Anthicidae	1	4	T	2	A
Mecoptera	1	4	T	3	A
Neuroptera	29	2, 5	T	1, 2, 3	LA
Sialidae					
Sialis spp.	21	1, 5	A	1, 3	L
Raphidiidae	6	2, 3, 4, 5	T	1	A
Hemerobiidae	3	2, 4	T	2, 3	A
Trichoptera	1,213	1, 2, 3, 4, 5	A	1, 2, 3	LPA
Limnephilidae	153	1, 2, 4, 5	A	1, 2, 3	LPA
Neophylax spp.	321	1, 2, 4, 5	A	1, 2, 3	L
Apatania spp.	5	1	A	1	L
Dicosmoecus spp.	56	1, 2, 5	A	1, 2, 3	LP
Ecclisomyia spp.	3	5	A	1, 2	L
Onocosmoecus spp.	6	1, 2	A	1, 3	L
Psychoglypha spp.	4	1, 2	A	2, 3	L
Limnephilus sp.	1	4	A	1	L
Philopotamidae	260	1, 2, 4, 5	A	1, 3	LPA
Wormaldia spp.	34	1, 2, 5	A	1, 2, 3	L
Dolophilodes spp.	3	1	A	3	L
Rhyacophilidae	9	1, 2, 4, 5	A	2, 3	LPA
Rhyacophila spp.	9	1, 2, 5	A	2, 3	LP
R. (nevadensis) group	4	5	A	1	L
R. (rotunda) group	9	1, 2	A	1, 2, 3	L
R. (sibirica) group	2	5	A	1, 3	L

Table 1—Invertebrates collected from Meadow Creek, Union County, Oregon, 1976-80 (continued)

Taxon	Number	Sample type[1]	Habitat type[2]	Season[3]	Life stage[4]
R. (coloradensis) group	7	1	A	1, 3	L
Hydropsychidae	139	1, 2, 4, 5	A	1, 2, 3	LA
Hydropsyche spp.	7,167	1, 2, 4, 5	A	1, 2, 3	LA
Psychomyiidae	3	2, 5	A	2, 3	LA
Psychomyia spp.	8	1, 5	A	3	L
Brachycentridae					
Amiocentrus spp.	9	2, 5	A	1	L
Micrasema spp.	5	1, 2, 5	A	1, 2, 3	L
Brachycentrus sp.	1	1	A	U	L
Lepidostomatidae					
Lepidostoma spp.	31,765	1, 2, 4, 5	A	1, 2, 3	LPA
Glossosomatidae	163	1, 2, 4, 5	A	1, 2, 3	LPA
Agapetus sp.	1	5	A	3	A
Glossosoma spp.	525	1, 2, 4, 5	A	1, 2, 3	LPA
Phryganeidae	1	4	A	3	A
Hydroptilidae	396	1, 2, 4, 5	A	1, 2, 3	LPA
Hydroptila spp.	40	1, 2, 5	A	1, 2, 3	L
Leucotrichia spp.	5	1, 2, 5	A	2, 3	L
Ochrotrichia spp.	87	1, 2, 5	A	1, 2, 3	L
Alisotrichia spp.	16	1, 2, 5	A	2, 3	L
Neotrichia spp.	9	1, 5	A	2	L
Stactobiella sp.	11	1, 2	A	1	L
Sericostomatidae					
Gumaga sp.	2	4	A	2	A
Helicopsychidae	8	1, 4, 5	A	2, 3	LPA
Helicopsyche spp.	40	1, 2, 5	A	1, 2, 3	L
Lepidoptera	466	1, 2, 3, 4, 5	A	1, 2, 3	LPA
Noctuidae	6	4	A	2	LA
Geometridae	16	2, 4	T	2, 3	LA
Pyralidae	779	1, 2, 4, 5	A	1, 2, 3	LPA
Diptera	47	1, 2, 4, 5	A	1, 2, 3	LPA
Nematocera	3	2, 5	A	2, 3	LA
Tipulidae	4,936	1, 2, 3, 4, 5	A	1, 2, 3	LPA
Antocha spp.	2,428	1, 2, 4, 5	A	1, 2, 3	LPA
Limnophila spp.	3,059	1, 2, 5	A	1, 2, 3	L
Dicranota spp.	77	1, 2, 4, 5	A	1, 2, 3	L
Tipula spp.	5	2, 5	A	3	L
Hexatoma spp.	1,305	1, 2, 5	A	1, 2, 3	L
Rhabdomastix spp.	5	1	A	1	L
R. fescigera Alexander	1	1	A	1	L
Gonomyia spp.	5	1	A	1	L
Psychodidae	183	1, 2, 3, 4, 5	A	1, 2, 3	LPA
Pericoma spp.	29	1, 2	A	1, 2, 3	L
Maruina sp.	1	5	A	1	L
Ptychopteridae (= Liriopeidae)	1	2	A	2	L
Blephariceridae	14	1, 2, 3, 4, 5	A	1	LPA
Deuterophlebiidae	58	1, 2, 3, 4, 5	A	1, 2, 3	LPA
Dixidae	42	2, 3, 4, 5	A	1, 2, 3	LPA
Dixa sp.	120	1, 2, 4, 5	A	2, 3	LP
Meringodixa sp.	6	2	A	3	L
Paradixa sp.	6	2	A	U	L
Culicidae	27	2, 4, 5	A	1, 2	PA
Ceratopogonidae (= Heleidae)	321	1, 2, 3, 4, 5	A	1, 2, 3	LPA
Atrichopogon sp.	1	5	A	3	L
Bezzia spp.	1,090	1, 2, 5	A	1, 2, 3	L
Chironomidae (= Tendipedidae)	32,484	1, 2, 3, 4, 5	A	1, 2, 3	LPA
Chironomini, tribe	4,326	1, 2, 4, 5	A	1, 2, 3	LP
Tanytarsini, tribe	10,360	1, 2, 4, 5	A	1, 2, 3	LPA
Pentaneurini, tribe	1,809	1, 2, 4, 5	A	1, 2, 3	LP
Macropelopiini, tribe	4	1	A	1, 3	L
Diamesini, tribe	97	1, 2, 5	A	1, 2, 3	LP
Orthocladiini, tribe	9,905	1, 2, 4, 5	A	1, 2, 3	LPA
Corynoneurini, tribe	605	1, 2, 4, 5	A	1, 2, 3	LP

Table 1—Invertebrates collected from Meadow Creek, Union County, Oregon, 1976-80 (continued)

Taxon	Number	Sample type[1]	Habitat type[2]	Season[3]	Life stage[4]
Simuliidae	506	1, 2, 3, 4, 5	A	1, 2, 3	LPA
Prosimulium spp.	215	1, 2, 5	A	1, 2, 3	LP
Simulium spp.	375	1, 2, 4, 5	A	1, 2, 3	L
Twinnia sp.	5	2	A	1	L
Bibionidae	76	2, 3, 4, 5	T	1, 2, 3	LA
Mycetophilidae	336	1, 2, 3, 4, 5	T	1, 2, 3	A
Sciaridae	1,375	1, 2, 3, 4, 5	T	1, 2, 3	LA
Scatopsidae	1	4	T	2	A
Cecidomyiidae	185	1, 2, 3, 4, 5	T	1, 2, 3	LA
Brachycera	174	2, 4, 5	A	1, 2, 3	LA
Acroceridae	2	4	T	1	A
Coenomyiidae	1	5	T	1	A
Stratiomyidae	5	1, 2, 5	A	1, 3	L
Tabanidae	118	1, 2, 5	A	1, 2, 3	L
Rhagionidae	96	1, 2, 3, 4, 5	T	1, 2, 3	LA
Atherix spp.	159	1	A	1, 2, 3	L
Asilidae	90	2, 3, 4, 5	T	1, 2, 3	A
Bombyliidae	5	4	T	1, 2	A
Empididae	1,705	1, 2, 3, 4, 5	T	1, 2, 3	LPA
Dolichopodidae	5,710	1, 2, 3, 4, 5	T	1, 2, 3	A
Cyclorrhapha	2,773	1, 2, 3, 4, 5	T	1, 2, 3	LPA
Lonchopteridae	6	1, 2, 4	T	2, 3	A
Phoridae	152	2, 3, 4, 5	T	1, 2, 3	LA
Pipunculidae	7	2, 4, 5	T	2	A
Syrphidae	19	2, 3, 4, 5	T	1, 2, 3	LA
Sepsidae	13	1, 2, 4, 5	T	1, 2, 3	A
Psilidae	10	2, 4, 5	T	1, 2	A
Sphaeroceridae	67	2, 4, 5	T	1, 2, 3	A
Milichiidae	12	1, 2, 4, 5	T	1, 2, 3	A
Ephydridae	2,684	1, 2, 3, 4, 5	A	1, 2, 3	LPA
Drosophilidae	30	1, 2, 4, 5	T	1, 2, 3	A
Chloropidae	28	1, 2, 4, 5	T	1, 2, 3	A
Agromyzidae	24	1, 2, 4, 5	T	1, 2, 3	A
Clusiidae	2	1, 5	T	1, 2	A
Heleomyzidae	38	2, 3, 4, 5	T	1, 2, 3	A
Camillidae	5	2	T	3	A
Sarcophagidae	6	4	T	2	A
Anthomyzidae	2	4, 5	T	1, 2	A
Dryomyzidae	2	4	T	2, 3	A
Platypezidae	2	2	T	3	A
Calliphoridae	9	3, 4	T	1, 2	A
Anthomyiidae	152	1, 2, 3, 4, 5	T	1, 2, 3	A
Muscidae	141	2, 3, 4, 5	A	1, 2, 3	LA
Scatophagidae	2	4, 5	T	2, 3	A
Tachinidae	85	4, 5	T	1, 2, 3	A
Hippoboscidae	1	4	T	3	A
Siphonaptera	2	4	A	2	A
Hymenoptera	141	2, 3, 4, 5	A	1, 2, 3	LA
Symphyta (= Chalastogastra)	19	2, 3, 4, 5	T	1, 2, 3	LA
Tenthredinidae	35	2, 4, 5	T	1, 2, 3	LA
Apocrita (= Clistogastra)					
Ichneumonoidea					
Ichneumonidae	195	1, 2, 3, 4, 5	A	1, 2, 3	A
Braconidae	32	2, 4, 5	A	1, 2, 3	A
Chalcidoidea	350	1, 2, 3, 4, 5	A	1, 2, 3	A
Mymaridae	4	4, 5	A	1, 2	A
Cynipoidea	8	2, 4	T	1, 2	A
Cynipidae	21	2, 5	T	1, 2, 3	A
Proctotrupoidea (= Serphaidea)	215	2, 3, 4, 5	T	1, 2, 3	A
Diapriidae	3	1, 2	A	2	A
Scelionidae	2	4	A	1	A
Bethyloidea					
Dryinidae	1	4	T	2	A
Scolioidea					

Table 1—Invertebrates collected from Meadow Creek, Union County, Oregon, 1976-80 (continued)

Taxon	Number	Sample type[1]	Habitat type[2]	Season[3]	Life stage[4]
Formicidae	1,[illegible]35	1, 2, 3, 4, 5	T	1, 2, 3	LA
Tiphiidae	1	4	T	2	A
Vespoidea	2	5	T	3	A
Vespidae	4	4	A	2, 3	A
Pompilidae	1	4	T	2	A
Sphecoidea					
Sphecidae	1	5	T	1	A
Apoidea	24	4, 5	T	1, 2, 3	A
Andrenidae	2	4	T	2	A
Halictidae	3	4	T	2	A

[1] Sample type: 1 = benthic; 2 = drift; 3 = sticky trap; 4 = water trap; 5 = stomach; U = unknown.
[2] Habitat type: A = aquatic; T = terrestrial; U = unknown.
[3] Season: 1 = spring; 2 = summer; 3 = fall; U = unknown.
[4] Life stage: L = larva; P = pupa; A = adult.

Literature Cited

Anderson, Norman H. 1976. The distribution and biology of the Oregon Trichoptera. Tech. Bull. 134. Corvallis, OR: Agricultural Experiment Station, Oregon State University. 152 p.

Baumann, Richard W.; Gaufin, Arden R.; Surdick, Rebecca F. 1977. The stoneflies (Plecoptera) of the Rocky Mountains. Memoirs of the American Entomological Society. 31: 1-208.

Borror, Donald J.; Delong, Dwight W.; Triplehorn, Charles A. 1976. An introduction to the study of insects. 4th ed. New York, NY: Holt, Rinehart and Winston. 852 p.

Bryant, Larry D.; Skovlin, Jon M. 1982. Effect of grazing strategies and rehabilitation on an eastern Oregon stream. In: Hashagen, K.A., ed. Habitat disturbance and recovery: Proceedings of a symposium. San Francisco, CA: California Trout, Inc.: 27-30.

Chess, James R. 1978. Some procedures for assessing organisms associated with rock substrata. In: Fish food habits studies: Proceedings of the 2d Pacific Northwest technical workshop. Wash. Sea Grant Publ. Seattle, WA: University of Washington: 25-28.

Cole, Frank R. 1969. The flies of western North America. Berkeley, CA: University of California Press. 693 p.

Edmunds, George F., Jr.; Jensen, Steven L.; Berner, Lewis. 1976. The mayflies of North and Central America. Minneapolis, MN: University of Minnesota Press. 330 p.

Hatch, Melville H. 1953. The beetles of the Pacific Northwest. Part 1: Introduction and Adephaga. Seattle, WA: University of Washington Press. 340 p.

Hatch, Melville H. 1957. The beetles of the Pacific Northwest. Part 2: Staphyliniformia. Seattle, WA: University of Washington Press. 384 p.

Hatch, Melville H. 1961. The beetles of the Pacific Northwest. Part 3: Pselaphidae and Diversicornia I. Seattle, WA: University of Washington Press. 503 p.

Hatch, Melville H. 1965. The beetles of the Pacific Northwest. Part 4: Macrodactyles, Palpicornes, and Heteromera. Seattle, WA: University of Washington Press. 268 p.

Hatch, Melville H. 1971. The beetles of the Pacific Northwest. Part 5: Rhipiceroidea, Sternoxi, Phytophaga, Rhynchophora, and Lamellicornia. Seattle, WA: University of Washington Press. 662 p.

Jensen, Steven Leroy. 1966. The mayflies of Idaho (Ephemeroptera). Salt Lake City, UT: University of Utah. 352 p. M.S. thesis.

Meehan, W.R.; Miller, R.A. 1978. Stomach flushing: effectiveness and influence on survival and condition of juvenile salmonids. Journal of the Fisheries Research Board of Canada. 35(10): 1359-1363.

Merritt, Richard W.; Cummins, Kenneth W., eds. 1978. An introduction to the aquatic insects of North America. Dubuque, IA: Kendall/Hunt Publishing Co. 411 p.

Miller, George Carl. 1960. The taxonomy and certain biological aspects of crayfish of Oregon and Washington. Corvallis, OR: Oregon State College. 216 p. M.S. thesis.

Pennak, Robert W. 1978. Fresh-water invertebrates of the United States. 2d ed. New York, NY: John Wiley and Sons. 803 p.

Richards, O.W.; Davies, R.G. 1977. Imms' general textbook of entomology. 10th ed New York, NY: John Wiley and Sons. 1,354 p.

Siebert, John; Kask, Beverly. 1978. Do fish have diets? In: Shepard, B.G.; Ginetz, R.M.J., Rapporteurs. Proceedings, 1977 Northeast Pacific chinook and coho salmon workshop; 1977 January 17-19; Vancouver, BC. Tech. Rep. 759. Vancouver, BC: Fisheries and Marine Service: 48-57.

Usinger, Robert L., ed. 1956. Aquatic insects of California. Berkeley, CA: University of California Press. 508 p.

Ward, Henry Baldwin; Whipple, George Chandler. 1959. Fresh-water biology. 2d ed. New York, NY: John Wiley and Sons. 1,248 p.

Wiggins, Glenn B. 1977. The larvae of the North American caddisfly genera (Trichoptera). Toronto, ON: University of Toronto Press. 401 p.

GPO 592-955/80082

McLemore, Carl E.; Meehan, William R. 1988. Invertebrates of Meadow Creek, Union County, Oregon, and their use as food by trout. Res. Pap. PNW-RP-394 Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 13 p

From 1976 to 1980, invertebrates were collected three times each year from several reaches of Meadow Creek in eastern Oregon. Five sampling methods were used: benthos, drift, sticky traps, water traps, and fish stomachs. A total of 372 taxa were identified, of which 239 were used as food by rainbow trout (steelhead; *Salmo gairdneri* Richardson). Of the taxa found in trout stomachs, 71 (29.5 percent) were terrestrial.

Keywords: Invertebrates, aquatic life, salmonids.

The **Forest Service** of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives—as directed by Congress—to provide increasingly greater service to a growing Nation.

The U.S. Department of Agriculture is an Equal Opportunity Employer. Applicants for all Department programs will be given equal consideration without regard to age, race, color, sex, religion, or national origin.

Pacific Northwest Research Station
319 S.W. Pine St.
P.O. Box 3890
Portland, Oregon 97208

March 1988

U.S. Department of Agriculture
Pacific Northwest Research Station
319 S.W. Pine Street
P.O. Box 3890
Portland, Oregon 97208

Official Business
Penalty for Private Use, $300

BULK RATE
POSTAGE +
FEES PAID
USDA-FS
PERMIT No. G

do NOT detach label

United States
Department of
Agriculture

Forest Service

Pacific Northwest
Research Station

Research Paper
PNW-RP-395
August 1988

Sport Fishing: A Comparison of Three Indirect Methods for Estimating Benefits

CLEMSON UNIVERSITY
OCT 5 1988
PUBLIC DOCUMENTS

Technical Editors

DARRELL L. HUETH was professor, Oregon State University, Department of Agricultural and Resource Economics, Corvallis, OR 97331; he is currently professor, University of Maryland, Department of Agricultural and Resource Economics, College Park, MD 29742. ELIZABETH J. STRONG was research assistant, Oregon State University, Department of Agricultural and Resource Economics, Corvallis, OR 97331; she is currently resource economist, Yuma, AZ. ROGER D. FIGHT is principal economist, USDA Forest Service, Pacific Northwest Research Station, Forestry Sciences Laboratory, P.O. Box 3890, Portland, OR 97208.

Sport Fishing: A Comparison of Three Indirect Methods for Estimating Benefits

Darrell L. Hueth,
Elizabeth J. Strong, and
Roger D. Fight,
Technical Editors

Published by:
U.S. Department of Agriculture, Forest Service,
Pacific Northwest Research Station,
Portland, Oregon
Research Paper PNW-RP-395
August 1988

Abstract

Hueth, Darrell L.; Strong, Elizabeth J.; Fight, Roger D., tech. eds. Sport fishing: a comparison of three indirect methods for estimating benefits. Res. Pap. PNW-RP-395. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station; 1988. 99 p.

Three market-based methods for estimating values of sport fishing were compared by using a common data base. The three approaches were the travel-cost method, the hedonic travel-cost method, and the household-production method. A theoretical comparison of the resulting values showed that the results were not fully comparable in several ways. The comparison of empirical results showed differences in values not easily accounted for on theoretical grounds. The data base was not designed to provide data for all three methods, and some of the resulting models explain only a small proportion of the variation.

Keywords: Recreational value, fishing, models.

Summary

We compared and critically evaluated three different market-based methods for estimating values of sport-fishing experiences. Values of particular interest were the average and marginal values of sport-caught salmon and steelhead in Oregon. Previous studies focused on average values of the fishing experience rather than on values of the fish catch. Values of fish may be useful in evaluating the efforts to protect and enhance fisheries.

The three methods we considered were the travel cost (both zonal-average and individual-observation versions), the hedonic travel cost, and the household production. All three methods are derived from a constrained utility-maximization problem, but they make different assumptions about an angler's process in making decisions, particularly about the role of quality characteristics of a site (such as the fishing success rate).

Empirical results are presented from four independent studies, each applying one method to data collected in a 1977 mail survey of Oregon anglers. Because the questionnaire was designed with the travel-cost method in mind, some difficulties were encountered in using the data to develop the other models. This, combined with not all the approaches being used to derive quite the same set of values, made a comparison of empirical results difficult. The household-production method was used only to estimate values for steelhead fishing, and the hedonic travel-cost method was used only to derive values for salmon fishing.

Results from the travel-cost model could be compared to those from the other two methods because the travel-cost method was used for both the salmon and the steelhead data. The value of a steelhead-fishing experience was greater in the travel-cost method than in the household-production method ($27 and $21, respectively) as was the value of a sport-caught steelhead ($155 and $84, respectively). The hedonic travel-cost method provided a higher estimate of the value of a salmon-fishing experience (ocean and river fishing combined) than did the travel-cost method ($177 and $141, respectively). Estimates of the value of sport-caught salmon were much closer—$254 and $248 from the hedonic travel-cost method and the travel-cost method, respectively.

We expected the results from the three models to differ, but not all the differences were easily accounted for by theory. This report outlines the theoretical conditions under which results should be similar, but value estimates in the models can also be affected by model specification, functional form, and valuation procedures.

One major outcome of this work was learning that a significant amount of preplanning in questionnaire design is necessary if a single data base will be used to estimate values by more than one method. In the early stages of any research effort to estimate recreational benefits, the scientist must determine and plan for theoretical assumptions, econometric procedures, and policy considerations. All three will affect the choice of approach and model specification, and these, in turn, will affect the types of data and experimental designs needed to produce the best results. Our primary intent was to provide researchers and potential users of value estimates with information to help them choose the best methods for their work.

Contents

1 Chapter 1: Introduction

2 Forest Management and Sport-Fishing Benefits

4 Project Objectives

4 Description of the Data

5 Organization of This Paper

6 Literature Cited

7 Appendix

11 Chapter 2: A Critical Review of Three Recreation-Valuation Methods

11 Introduction

12 Theoretical Basis

12 The Travel-Cost Method

13 The Hedonic Travel-Cost Method

16 The Household-Production Method

18 Econometric Considerations

19 The Travel-Cost Method

20 The Hedonic Travel-Cost Method

21 The Household-Production Method

22 Constructing the Price Variable

24 The Aggregation Problem

26 Policy Considerations

27 Summary

29 Literature Cited

31 Chapter 3: Empirical Results From the Travel-Cost Model: Zonal-Average and Adjusted Individual-Observation Versions

31 Theoretical Relationships Between Angler Benefits and Fish Catch

32 **Estimated Zonal-Average Travel-Cost Demand and Benefits**

32 Freshwater Salmon Angling

37 Steelhead Angling

39 Ocean Salmon Angling

40 **Effect of Other Factors on Estimated Benefits Per Fish**

42 **Estimated Demand and Benefits Based on Adjusted Individual Observations Per Capita**

42 Freshwater Salmon Angling

44 Ocean Salmon Angling

44 **Summary and Conclusions**

45 **Acknowledgment**

46 **Literature Cited**

47 Chapter 4: Empirical Results From the Travel-Cost Model: Individual-Observation Approach

48 **Estimated Demand and Benefits**

48 Freshwater Salmon Angling Based on Unadjusted Individual Observations

48 Ocean Salmon Angling

49 **Literature Cited**

50 Chapter 5: Fitting the Travel-Cost Model by Using Zonal Averages, Individual Observations, and Adjusted Individual Observations

50 **Part I: Potential Weaknesses of the Unadjusted Individual-Observation Travel-Cost Model**

56 **Part Ii: Potential Weaknesses of the Zonal-Average and Adjusted Individual-Observation Travel-Cost Models**

58 **Literature Cited**

59 Chapter 6: Valuing Oregon Steelhead by Using a Household-Production Approach

60 Household-Production Method

64 The Conceptual Model for Steelhead Fishing

68 Estimated HP Model Excluding Policy-Related Variables

73 Estimated HP Model Including Policy-Related Variables

79 Summary

80 Literature Cited

81 Chapter 7: Valuing Oregon Salmon by Using a Multimarket, Hedonic Travel-Cost Method

82 The Hedonic Travel-Cost Method

84 Data and Variables

84 Data

84 Variables

85 Estimation

91 Conclusions

92 Literature Cited

92 Appendix

93 Chapter 8: Further Comparison of Results From Three Recreation-Valuation Methods

94 Comparability of Results

94 Value of a Fishing Experience

95 Value of a Sport-Caught Fish

96 Comparison of Some of the Empirical Results

96 Average Values for Salmon Fishing

98 Average Values for Steelhead Fishing

99 Conclusion

Chapter 1: Introduction

Darrell L. Hueth, Elizabeth J. Strong, and William G. Brown[1]

Forest managers are concerned not only with timber harvest but also with alternative uses of forests, such as preservation of wildlife in wilderness areas, protection of streams, reforestation, and recreation. Rational management decisions can be made if the prices of all alternative uses are available. The value of timber is the most easily calculated because timber eventually passes through the market system. Values for recreational activities, such as fishing, hunting, and river rafting, are much more difficult to estimate. We examined three ways to estimate values of one recreational activity in Oregon—sport fishing.

Values of particular interest are the average and marginal values of sport-caught steelhead and salmon. Most earlier studies (for example, Brown and others 1964, Wennergren 1967) focus on values of recreational experiences and recreational sites and not on values of fish caught.[2] Estimates of marginal values associated with marginal changes in fish catch have therefore not been available.

[1] DARRELL L. HUETH was professor, Oregon State University, Department of Agricultural and Resource Economics, Corvallis, OR 97331; he is currently professor, University of Maryland, Department of Agricultural and Resource Economics, College Park, MD 29742. ELIZABETH J. STRONG was research assistant, Oregon State University, Department of Agricultural and Resource Economics, Corvallis, OR 97331; she is currently resource economist, Yuma, AZ. WILLIAM G. BROWN is professor, Oregon State University, Department of Agricultural and Resource Economics, Corvallis, OR 97331.

[2] An exception to this statement is an innovative, recent study by Samples and Bishop (1985) in which they estimate the value of differences in success rates of anglers at various sites by relating estimated consumer surplus to success rates at the various sites. We essentially followed the approach of Samples and Bishop except that we related the value of differences in fish catch, based on differences in estimated consumer surplus, to fish catch from river to river.

Some crude average values can be obtained from travel-cost studies by dividing the estimated total consumer surplus by the total sport harvest of fish or game, but the validity of using such values to make marginal decisions affecting fish and game abundance and harvest has been justifiably questioned. If sport-fishing effort can be regarded as independent of fish catch, then the average values are important for knowing how marginal changes in fish abundance affect the value of sport fishing.

If no knowledge of marginal fish values is available, an efficient allocation of public funds and natural resources is unlikely. For example, if the value of salmon and steelhead sport fishing in the Pacific Northwest is unrelated to fish catch, then there is no economic justification for public expenditures on fish hatcheries and stream improvement to enhance, or to even maintain, salmon and steelhead runs, at least so far as angler benefits are concerned. On the other hand, if a strong positive relation between fish catch and the benefits from salmon and steelhead sport fishing exists, then use of public resources to protect or enhance the runs can be justified. In either case, there are important noneconomic reasons to maintain salmon and steelhead runs.

Forest Management and Sport-Fishing Benefits

The value of forest streams in sport fishing can be both directly and indirectly influenced by forest land-management practices. Direct effects result when forest land-use decisions influence the scenic attributes of the fishing site that, in turn, influence the attractiveness of a site for sport fishing. Some environmental quality changes not perceived by anglers still have indirect effects on angler demand; for example, indirect effects result when changes in water quality caused by forest-management activities influence the abundance or catchability of fish in a stream. These are called indirect effects because, unlike the scenic attributes of a site, they may not cause anglers to derive direct pleasure out of a productive habitat or clear water but to benefit indirectly by catching more fish.

Figure 1 illustrates a system that relates forest management to benefits of sport fishing. The arrows indicate the directions of causation; for example, the upper part of the diagram shows that forest-management practices (that is, logging or road construction) near a stream might affect the attractiveness of fishing sites to anglers. Reduced scenic quality of a site may directly reduce use of the site, as measured by the number of fishing trips taken. Additional logging roads could result in increased use of forest streams, however, by making remote sites more accessible, particularly if anglers do not make scenery a high priority when choosing a site.

The left side of figure 1 shows that logging and road construction can also reduce water quality in forest streams. Such changes might lead to immediate reductions in the catchability of fish, the stocks of young and adult fish, and the productivity of fish habitats. Changes in fish catchability and adult fish stocks immediately affect the number of fish an angler can catch with the same amount of effort; changes in smolt survival and productivity of the habitat cause delayed effects on the productivity of anglers in catching fish.

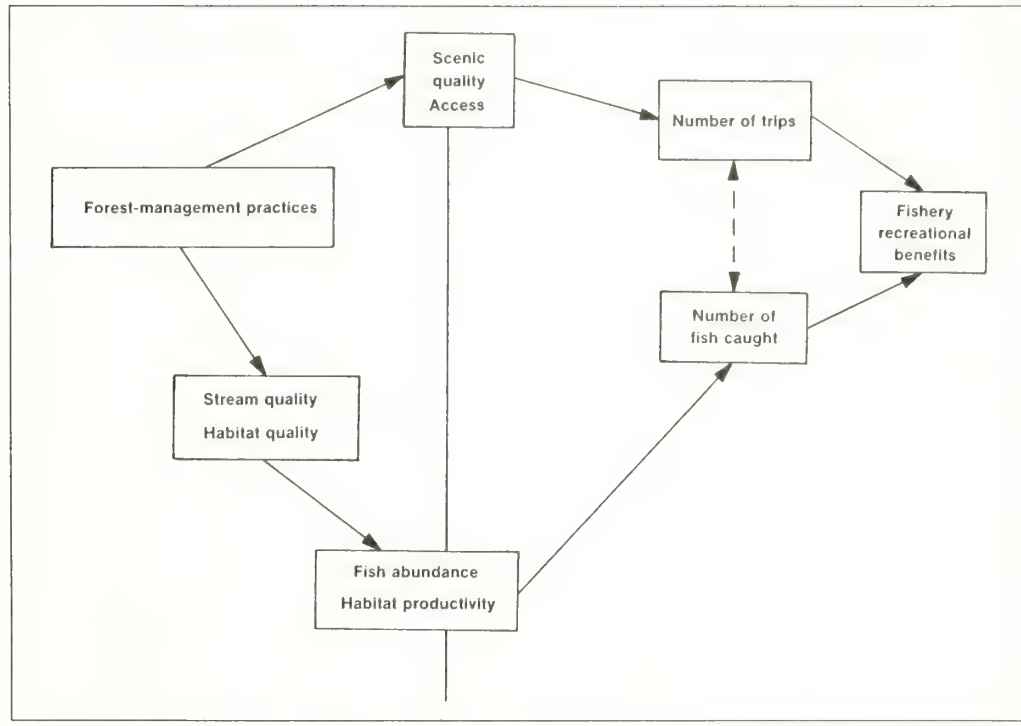


Figure 1—A conceptual model of the direct and indirect effects of forest-management policies on recreational benefits.

Finally, changes in the fishing success rate at a site affect the value of that site resource as a sport fishery. This value is measured, by nonmarket valuation techniques, as the benefits anglers receive from visiting the site. In some nonmarket valuation models, the number of fish caught is viewed as directly generating recreational benefits; in other models, effects of fish catch are viewed as moving in the direction of the dashed arrow (see fig. 1) and indirectly affecting recreational benefits by changing the number of trips taken.

Forest resource managers have trouble developing and empirically testing a model such as that suggested in figure 1. Biologists, hydrologists, and fishery and forest resource managers want to work with economists to determine economic values for fish populations, but only limited progress has been made. So far, the first part of the system (to the left of the vertical solid line in fig. 1), which relates logging activities to stream quality, has seen the most research (Brown 1976, Chamberlain 1982). A notable research effort in Oregon identified changes in sediment concentration, dissolved oxygen concentration, water temperature, and streamflow as some of the direct consequences of timber harvesting and road construction (Moring and Lantz 1975). Because these attributes are important to anadromous fish habitat, logging-induced quality changes are believed to influence anadromous fish production. Although well-documented evidence of logging-induced changes in the physical quality of Pacific coast streams exists, the complexity of river and estuarine ecosystems has slowed research on the environmental impacts of logging on productivity of anadromous fisheries. Efforts to develop models that estimate logging-stream quality relationships have also been hampered by the complexity of forest ecosystems and by the difficulties in extrapolating the observed relationships from one river system to another in a different geographic area.

As we said, the relationship between water-quality parameters and angler benefits is indirect; that is, they are mainly related through the effects of water-quality changes on fish abundance and, hence, the number of fish caught. To make the connection between forest-management practices and the benefits of sport fishing, the link must be established between water quality and fish abundance. At present, little information is available on that link.

Most valuation models for recreation have begun with data on items to the right of the vertical solid line (see fig. 1); that is, they have been designed to measure the relationship between fishing activities and the value of fishery resources. We extended the analysis to measure the relationship between fish catch and the value of fishery resources to estimate the value of a sport-caught fish. In addition, the household-production method presented in this paper is, perhaps, the first attempt to establish an empirical relationship between habitat quality and fish catch, which can then be used to estimate the effects of changes in water quality on recreational values.

Two general approaches are used to measure recreational benefits of fishing. The first, contingent valuation, uses direct interviewing to elicit values from users and potential users of recreational sites. The second, a market-based approach, uses actual expenditures on marketed goods and posits relationships between these goods and recreational activities to estimate recreational benefits.

Project Objectives

The objective of our research was to compare and evaluate three market-based methods for estimating values of recreational fishing by using one common data base. Data obtained from a 1977 survey of Oregon anglers, which is described below, was used to estimate values by using the travel-cost method (TC), the hedonic travel-cost method (HTC), and the household-production method (HP). The data base was used to estimate both the traditional zonal-average travel-cost and the individual-observation travel-cost models, both adjusted and unadjusted.

A second objective of this research was to provide estimates of average and, where possible, marginal values of salmon and steelhead. These values are important in forest-management decisions and also in other settings, particularly in the evaluation of projects to enhance fish production in a river system.

Description of the Data

A sample of 9,000 anglers was drawn from purchasers of Oregon angling licenses during 1977. This sample was about 1.5 percent of the total licenses sold, including in-State and out-of-State licenses of all categories. A questionnaire was used to obtain quarterly data from the anglers about their fishing-related expenditures and fishing activities. Questionnaires were mailed at the end of each quarter during 1977. For the first quarter, January 1 through March 31, 1,200 questionnaires were sent; 2,700 were sent out for the second quarter; 3,600 for the third quarter; and 1,500 for the fourth. We anticipated we would receive more information from the survey by concentrating the sampling in the most active fishing seasons—spring and summer.

An extensive followup by mail and telephone resulted in a return of 55.6 percent. Besides nonrespondents being reminded by telephone to complete and return the questionnaires, any respondent whose questionnaire was incomplete or suspected of being erroneous in some respect was also telephoned. Although this procedure was costly and time consuming, the quality of the information from the survey was greatly improved by the telephone followup. More detailed information about the survey design is reported by Sorhus (1980) and Sorhus and others (1981). A copy of the questionnaire is in the appendix to this chapter.

Organization of This Paper

Chapter 2 presents a critique of the methods based on the theoretical foundations of angler's choices, statistical and econometric considerations, data requirements, and policy implications (that is, what questions each method is best able to answer). Chapters 3, 4, 6, and 7 present the results of using each method to estimate recreational benefits. Chapter 5 provides additional comments on the strengths and weaknesses of zonal-average, individual-observation, and adjusted individual-observation formulations of the travel-cost method. Chapter 8 compares, insofar as possible, the empirical results from using the three basic techniques.

Literature Cited

Brown, George W. 1976. Forestry and water quality. Corvallis, OR: Oregon State University Book Stores, Inc. 73 p.

Brown, William G.; Singh, Ajmer; Castle, Emery N. 1964. An economic evaluation of the Oregon salmon and steelhead sport fishery. Tech. Bull. 78. Corvallis, OR: Oregon Agricultural Experiment Station. 47 p.

Chamberlain, T.W. 1982. Timber harvest. Gen. Tech. Rep. PNW-136. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 30 p. (Meehan, William R., tech. ed.; Influence of forest and rangeland management on anadromous fish habitat in Western North America; pt. 3).

Moring, John R.; Lantz, Richard L. 1975. The Alsea watershed study: effects of logging on the aquatic resources of three headwater streams of the Alsea River, Oregon, part 3: Changes in environmental conditions. Fisheries Res. Rep. 9. Corvallis, OR: Oregon Department of Fish and Wildlife. 24 p.

Samples, Karl C.; Bishop, Richard. 1985. Estimating the value of variations in anglers' success rates: an application of the multiple-site travel cost method. Journal of Marine Resource Economics. 2(1): 55-74.

Sorhus, Colin N. 1980. Estimated expenditures by sport anglers and net economic values of salmon and steelhead for specified fisheries in the Pacific Northwest. Corvallis, OR: Oregon State University. 142 p. Ph.D. thesis.

Sorhus, Colin N.; Brown, William G.; Gibbs, Kenneth C. 1981. Estimated expenditures by salmon and steelhead sport anglers for specified fisheries in the Pacific Northwest. Spec. Rep. 631. Corvallis, OR: Oregon Agricultural Experiment Station Special Report 631. 86 p.

Wennergren, E. Boyd. 1967. Demand estimates and resource values for resident deer hunting in Utah. Sta. Bull. 469. Logan, UT: Utah Agricultural Experiment Station. 44 p.

Appendix

OREGON FISHING ACTIVITIES QUESTIONNAIRE

1. Did you, yourself, go fishing *in Oregon* any time during the last 3 months (January-March 1977), or not?
   ____ Yes, fished. (Go to Question 2) ____ No, did not fish. (Go to Question 5)

2. How many times did you go fishing from January through March 1977? ____ Number

3. Of these trips, how many were intended primarily as fishing trips, as contrasted to trips taken mainly for other reasons (but where some fishing was done)? ____ Number.

4. Of all your fishing trips, how many were primarily for steelhead? ____ Number.
   How many were primarily for salmon fishing? ____ Number.
   How many for resident trout? ____ Number.
   How many for any other species? (Please specify _____) _____ Number

5. What type of fishing license(s) did you, yourself, purchase for 1977? (Please check all that apply.)

   - ☐ Resident Combination
   - ☐ Resident Combination with bow
   - ☐ Resident Angler
   - ☐ Juvenile Angler
   - ☐ Nonresident Angler
   - ☐ 10-day Angler
   - ☐ 1-day Angler
   - ☐ 2-day Angler
   - ☐ 3-day Angler
   - ☐ Pioneer Angler
   - ☐ Disabled Vet Angler
   - ☐ Senior Citizen Angler

6. In addition, did you purchase a salmon-steedhead tag? ____ Yes ____ No

7. What is *your* approximate age?

   - ☐ Under 21
   - ☐ 21-29
   - ☐ 30-39
   - ☐ 40-49
   - ☐ 50-59
   - ☐ 60-69
   - ☐ 70 years or over

8. How many people, including yourself, are in your household and living at home at the present time? ____ Number.

9. Please indicate the average number of hours, if any, you were working for pay during the last three months. Please check if you are retired or are a student.

   ____ Number of hours worked per week.
   ____ Retired.
   ____ Student.

10. Which of the following categories most closely corresponds to the combined yearly income, before taxes, for *all* members of your household for 1976?

    - ☐ Under $3,000
    - ☐ $3,000-$ 4,999
    - ☐ $ 5,000-$ 7,999
    - ☐ $ 8,000-$11,999
    - ☐ $12,000-$14,999
    - ☐ $15,000-$17,999
    - ☐ $18,000-$ 24,999
    - ☐ $25,000-$ 34,999
    - ☐ $35,000-$ 49,999
    - ☐ $50,000-$100,000
    - ☐ Over $100,000

(PLEASE TURN TO PAGE 2 IF YOU FISHED IN JANUARY-MARCH 1977:
PLEASE TURN TO PAGE 4 IF YOU DID NOT)

PLEASE ANSWER THE FOLLOWING QUESTIONS (11-21) ABOUT YOUR LAST 3 *OREGO*
IF YOU TOOK LESS THAN 3 TRIPS, PLEASE FILL IN ONLY THE QUEST

11. Write name of river, stream, or name of lake (or ocean) where this fishing trip took place .....

12. In what county was this port, river, lake, or stream where you fished? (See map on back of introductory letter) .....

13. How many miles did you travel, one way, on your fishing trip? .....

14. Did you make this trip in an automobile or a pickup without a camper?
Circle YES or NO .....

15. Did you make this trip in a motor home, auto with camper, or a pickup camper?
Circle YES or NO .....

16. How many hours (or days) did you spend at your destination? .....

17. When you were developing your plans for this trip, what was the shortest length of time you would have considered staying at your destination, in hours (or days)? .....

18. How many *hours* did you actually fish? (If for more than one species, divide the time among species):
STEELHEAD .....
SALMON .....
RESIDENT TROUT .....
SEA-RUN CUTTHROAT .....
WARM WATER GAME FISH .....
OTHER .....

19. How many fish of each species did you, yourself, catch?
STEELHEAD .....
SALMON .....
RESIDENT TROUT .....
SEA-RUN CUTTHROAT .....
WARM WATER GAME FISH .....
OTHER .....

20. How many people went with you on this trip? .....

21. Approximately how much did you *and your group* spend for the following items? (Just your best estimate)
(a) Food, drink (including liquor), bought in restaurants, bars, or taverns, while traveling to and from your destination .....
(b) Food and drink bought in restaurants, bars, and taverns while at your destination .....
(c) Total amount spent for camping fees, lodging in motels and hotels, while traveling to and from your destination .....
(d) Amount spent for camping fees and lodging while at your destination .....
(e) Guide service, bait, and lures .....
(f) Rental of fishing tackle, equipment, boat, and/or motor .....
(g) Boat launching fees .....
(h) Gallons of gas used in your boat (do not include rental boats and motors) .....
(i) Other *rental* items (Specify) _____ .....
_____ .....
(j) Miscellaneous expenses (Specify) _____ .....
_____ .....

ON FISHING TRIPS DURING THE PERIOD JANUARY THROUGH MARCH 1977.
IONS REFERRING TO THE NUMBER OF TRIPS YOU TOOK.

TRIP 1	TRIP 2	TRIP 3
_____	_____	_____
_____	_____	_____
_____	_____	_____
YES _____ _____ NO	YES _____ _____ NO	YES _____ _____ NO
YES _____ _____ NO	YES _____ _____ NO	YES _____ _____ NO
_____ hours _____ days	_____ hours _____ days	_____ hours _____ days
_____ hours _____ days	_____ hours _____ days	_____ hours _____ days
_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____
$ _____	$ _____	$ _____
$ _____	$ _____	$ _____
$ _____	$ _____	$ _____
$ _____	$ _____	$ _____
$ _____	$ _____	$ _____
$ _____	$ _____	$ _____
$ _____	$ _____	$ _____
_____ gals.	_____ gals.	_____ gals.
$ _____	$ _____	$ _____
$ _____	$ _____	$ _____
$ _____	$ _____	$ _____
$ _____	$ _____	$ _____

PLEASE GO ON TO NEXT PAGE

22. Listed below are items often used by fishermen. Please record your expenditures for equipment, regardless of when purchased, that you still use in your Oregon fishing activities. To see how to complete percents for the last two columns, please refer to the following example:

EXAMPLE: Assume you purchased a boat, and use it a total of 100 hours per year. Of this 100 hours, 50 hours were used for all angling, of which 25 hours were for salmon and steelhead angling. In this case, 50% should be allocated to *all* angling, and 25% should be allocated to salmon and steelhead fishing.

Item	Purchase price	Year(s) in which purchased	State in which purchase was made	Replacement cost today	Percent of time item is used for all fishing	Percent of time item is used for salmon and steelhead fishing
	dollars			*dollars*	%	%
Tackle:						
Rod(s)	$			$	100	
	$			$	100	
	$			$	100	
Reel(s)	$			$	100	
	$			$	100	
	$			$	100	
Creel(s)	$			$	100	
Tackle box(es)	$			$	100	
Landing net(s)	$			$	100	
Any other tackle	$			$	100	
Boating equipment:						
Boat(s)	$			$		
Boat trailer(s)	$			$		
Outboard motor(s)	$			$		
Any other	$			$		
Special clothing:						
Waders, Hipboots	$			$		
Fishing vest(s)	$			$		
Coat(s)	$			$		
Rainwear	$			$		
Any other	$			$		
Camping equipment:						
Tent(s)	$			$		
House trailer	$			$		
Camper(s)	$			$		
Pickup truck(s)	$			$		
Sleeping bags	$			$		
Lantern(s)	$			$		
Stove(s)	$			$		
Any other	$			$		
Other equipment expenditures not listed above; (specify):						
_____	$			$		
_____	$			$		

Is there anything else you would like to say about fishing in Oregon? Please return questionnaire and any comments you would like to make in envelope provided.

THANK YOU FOR YOUR COOPERATION.

independently of one another and do not compete with one another for visitors but are instead controlled by a single, hypothetical owner, and the technology for this owner is described by a single hedonic price function. It follows from this assumption that the HTC method implicitly assumes that production conditions are identical across sites providing services to a given zone. The implicit price equations can, therefore, be viewed as identifying characteristic supply curves for the single hypothetical producer.

With the HTC technique, the structure of consumer preferences is identified by fitting demand equations for characteristics. To trace out demand equations for characteristics, a sufficiently large number of supply curves for each characteristic are needed. Because each hedonic price function describes the production technology for a different zone of origin, the supply curves for characteristics will differ across zones. (A given site will have more than one supply curve for each characteristic if that site supplies services to more than one zone.) Thus, the characteristic supply curves across zones are used to identify characteristic demand equations for a representative zone.

The fitted supply and demand equations for characteristics can be used to obtain estimates of the value of a recreational experience and benefits to recreationists from changes in implicit prices. Because the HTC method assumes that characteristic supplies are exogenously determined, estimates of the benefits to recreationists of marginal changes in the supply of characteristics can also be obtained. This is equivalent to evaluating the benefits of changes in implicit characteristic prices because shifts in supply result in changes in equilibrium prices. The assumption must be made that these changes automatically lead to equivalent changes in the demand for characteristics in order to evaluate the benefits of changes in characteristic supplies.

Either the demand equation for characteristics or the demand equation for visits can be used to obtain an estimate of the value of a recreational experience. In the visits market, estimates of recreational benefits are calculated in the same way as they are in the TC demand model, discussed above; that is, the total area under the demand curve for visits and above the horizontal price line gives an estimate of total benefits for the recreationist. This measure of total benefits is divided by the number of visits to obtain an estimate of the average value of a recreational experience.

The above procedure is equivalent to estimating the benefits of sequentially increasing implicit characteristic prices from their current equilibrium levels to the points at which the quantity demanded of each characteristic just reaches zero.[6] This is true because an increase in the price of a visit (p_v) to the point where the demand for visits just falls to zero automatically causes the demand curve for each characteristic to shift to the left until the quantity demanded at the given equilibrium implicit price just reaches zero.

---

[6] A necessary condition for measuring benefits of changes in p_v in characteristics markets is that: $\partial U / \partial v \mid_{z_1,\ldots,z_m = 0} = 0$. By using the sequential procedure for evaluating the benefits of multiple price changes, one can calculate the sum of changes in areas under the demand curves in all markets experiencing price changes. In each market, the demand curve is conditioned on all previously considered price changes.

The existence of implicit markets for quality characteristics in the HTC model is what distinguishes this model from the traditional TC model. Implicit prices are derived for characteristics (treated as choice variables), but these prices are assumed to be either constant or dependent only on the supplies of characteristics, which are assumed to be fixed at each site. Technological factors influence the supply of characteristics at a given site, however, and these factors tend to differ from one site to another; for example, the technological factors that may influence the supply of a fishing success-rate characteristic include the stock of fish and the quality and quantity of fish habitat. For scenery, the technological factors might include the density of trees along the river, the geographic features of the surrounding area, and the number of acres of wilderness adjacent to the river (or the ratio of wilderness to developed acres). These technological factors at any given site may be fixed in the short run, but they might be altered in the long run. Changes in technology will result in shifts in characteristic supply curves. Any such relationships between technological conditions and utility-yielding quality characteristics must be specified outside the HTC model.[7]

The Household-Production Method

The HP method is not necessarily restricted by the inability to endogenously specify relationships between technological factors and quality characteristics. A cost function is specified for those characteristics partially controllable by recreationists (henceforth called endogenous characteristics). If exogenous technological factors were included in the cost function, then the marginal cost (supply) equations for the endogenous characteristics would depend on these technological factors. Hence, the relationships between technological (that is, environmental) conditions at a site and the supplies of endogenous characteristics may be specified directly within the model. This means that the HP framework can be used to estimate the benefits to recreationists of exogenous changes in technology (or environmental quality).

In the HP framework, the recreationist is taken to be both a producer and a consumer of nonmarket goods (commodities). In Bockstael and McConnell's (1983) formulation of the HP model for sport fishing, the angler is assumed to both produce and consume the fish-catch rate (measured in terms of catch per trip or catch during a given period). Given the environmental conditions at the site, the available fishing equipment, and the angler's level of experience, the fish-catch level (z_1) can be produced by combining purchased fishing goods and fishing time. The angler is also assumed to both produce and consume the fishing trips taken during the given period. Total fishing trips (v) are produced by combining purchased transportation goods and travel time. Technological factors that may influence how many trips the angler takes with a given bundle of inputs include the distance between the angler's residence and the site, and the transportation used.

---

[7] Rosen (1974) shows that when firms are not identical, the cost function is defined on attributes that differ from one firm to another, such as factor prices and technological conditions. The structure of production can then be identified through fitting characteristic supply equations derived from the cost function. The implicit price equations in such a model merely connect the points of intersection of supply and demand curves. To fit the hedonic price equation, observed prices are simply regressed on characteristic quantities by using the best fitting functional form. This procedure does not seem to be applicable for developing the HTC model because no actual producer of characteristics exists that a cost function can be defined for. "Production costs" in this framework are borne by the consumer.

Marginal costs are treated as implicit prices for commodities in this framework and give the minimum costs for obtaining one more unit of a commodity. Marginal costs are derived by partially differentiating the cost function for each commodity. In the HP model, as in the HTC model, the optimal price-quantity combination in each commodity market is defined at the point of intersection of supply and demand curves. But unlike the HTC method, the HP method does not use the price of a fishing experience to infer implicit prices for endogenous quality characteristics, such as the fishing-success rate. Instead, the HP method separates the fishing experience into two parts—the fishing trip itself and the sport-caught fish. A separate, but not necessarily independent, implicit price (or marginal cost) function is specified for each of these commodities.

Given the implicit price (supply) functions for fishing trips (v) and sport-caught fish (z_1), one can derive the commodity demand equations by maximizing utility, $U = U(v,z_1,\bar{z},y)$, subject to the implicit budget constraint, $I = p_v v + \pi_1 z_1 + y$, where p_v and π_1 are equilibrium-implicit prices and $\bar{z}$ denotes exogenous quality characteristics. The demand equations for fishing trips and fish catch at a given site during a given period are defined on the implicit prices for v and z_1 and on the exogenous quality characteristics ($\bar{z}$) and implicit income (I). They are written as:

$$v = G_v(p_v(r_v,w,v,e_v), \pi_1(r_1,w,z_1,e_1),\bar{z},I) \text{ , and}$$

$$z_1 = G_1(p_v(r_v,w,v,e_v), \pi_1(r_1,w,z_1,e_1),\bar{z},I) \text{ ,}$$

where r_v and r_1 are market prices for the market transportation and fishing goods, respectively; w is the opportunity cost of both travel and fishing time; and e_v and e_1 are technological conditions influencing angler productivity in each commodity market. Environmental conditions at the site, such as fish density and water quality, may be included as exogenous technology variables in e_1. Several different procedures can be used to estimate the benefits to anglers from changes in exogenous quality variables that appear in the cost function. These procedures are described by Bockstael and McConnell (1983) and Strong (1983).

In the HP model, the angler derives utility from both taking a fishing trip and catching fish. The value of a fishing experience is therefore equal to the combined value of the trip and the sport-caught fish. The average value of a fishing experience is estimated by summing total benefits in both markets and dividing by the number of trips taken. Average values of a sport-caught fish can be estimated by calculating total benefits in the fish-catch market alone and dividing this benefit by the number of fish caught. Because fish catch is treated as an endogenous variable, the marginal value of a sport-caught fish cannot normally be determined in this framework as it can by using the TC and HTC methods.

The HP model is different than the TC and HTC models for sport fishing in that the shadow price per trip is not assumed to be fixed; it is also not assumed that the fish-catch rate at any site is outside the control of anglers. The TC method treats the fish-catch rate as an exogenous quality variable that is weakly complementary to visits, and the HTC method treats it as a choice variable with the supply fixed at any given site. Other quality characteristics that can be treated as choice variables in the HTC model include scenery and congestion. These quality characteristics are treated as exogenous quality variables rather than as endogenous choice variables in both the TC model and the HP model (as part of $\bar{z}$). If the fish-catch rate (z_1) is treated as part of $\bar{z}$ (that is, as an exogenous but utility-yielding quality variable), and if the implicit price of a trip is constant, then the HP model collapses to the TC model, as pointed out by Bockstael and McConnell (1981).

Econometric Considerations

We compared the three methods on econometric considerations, including data needs, estimation techniques, and possible specification biases. The methods were ranked by how much control the recreationist is assumed to have over the quality of the experience. The recreationist is assumed to have least control in the TC method and most control in the HP method. With more control, however, comes more extensive data requirements and greater analytical difficulty. Indeed, as we will show, the TC method requires the least basic data and is generally the easiest method to apply. We found the HP technique to be at the other end of the scale and to require considerably more data and analytical steps for the best results. Analytical difficulties may arise with the HP method in attempts to obtain solutions to highly nonlinear systems of equations. For data requirements and degree of analytical difficulty, the HTC method seems to lie somewhere between the TC and HP methods.

The three methods were compared as if each were applied to develop a model for sport fishing. The common-choice variable in each model was defined as the number of fishing trips taken to a given site. Only one quality characteristic –the rate of fishing success—was used to simplify the discussion. Two reasons for including a catch-rate variable in the model are to obtain estimates of the value of sport-caught fish and estimates of the recreational benefits of changes in either fish catch or the implicit price of a sport-caught fish. We assumed that the utility function underlying each approach was weakly separable in sport-fishing commodities, so that prices of other commodities could be omitted from the demand equations. We also assumed that the TC and HP models were developed for a representative site rather than for multiple sites.

The Travel-Cost Method

A single demand equation is specified for fishing trips to apply the TC method to develop a single-site model. If data are available for several sites, a separate demand equation for each site can be developed or the data can be pooled across sites and a demand equation fitted for a typical site in the sample. For the basic model, data are required to construct variables on the number of fishing trips taken to a given site, the fixed price of a visit, and the income of the user. The price variable is frequently defined as the product of round-trip distance and some fixed cost per mile for transportation. Sometimes the price variable is constructed from actual data on reported per-trip expenditures. The opportunity cost of round-trip travel time can also be included in the price variable.[8]

If the price per visit is defined as the sum of transportation expenses plus the opportunity cost of travel time, then it must be assumed that marginal variations in money and time costs have an identical effect on the demand for fishing trips. It is also assumed that the cost function is linear in the trips variable because the marginal cost equation for trips would be written as $MC_v = m_v + t_v$, where m_v denotes monetary travel costs and t_v is the time cost per trip. If time costs are included in p_v, then the budget constraint (and, hence, the income variable) should include the value of available time, as well as the amount of available money income.

Quality characteristics of a fishing experience (such as the fishing success rate) can be included as exogenous variables in the TC demand equation; but for a fish-catch-rate variable, this approach causes problems. A correlation between the error term of the estimated demand equation and the catch-rate variable is likely and can arise from a correlation between errors of measurement in this variable and the dependent variable.[9] This correlation tends to cause biased parameter estimates. One way to correct for these potential biases is by using an instrumental variable technique.[10]

---

[8] The subject of which cost categories to include in the travel-cost variable has received considerable attention in the literature. Hammack and Brown (1974) argue that only cost differentials among recreationists need to be included and that any costs common to all users can be safely omitted. They show that these costs affect only the intercept of the travel-cost demand equation and predict that visits and consumer surplus are the same whether these common costs are included or not. The only difference when common costs are included is that the price paid is higher.

Ward (1984) argues that including any endogenous variables in the construction of the travel-cost variable is likely to result in bias in the estimated price coefficient. He does, however, include exogenous costs—in particular, any entry fees paid at the site—common to all users. Including these common entry fees seems appropriate if the analyst is interested in valuing the site; that is, consumer surplus is the same with or without including these costs, but the value of the site is underestimated if they are excluded.

[9] This problem is discussed in an unpublished paper presented at the Allied Social Science Meetings, New York, December 20-30, 1982, "Estimation of Oregon Sport Caught Salmon and Steelhead Values Via the Travel Cost Method," by William G. Brown, Colin N. Sorhus, and Philip A. Meyer.

[10] If the price variable for visits is calculated by using data on reported expenditures, then the same kind of correlation may also occur between measurement errors in the dependent variable and in the price variable. Using distance traveled and a constant travel cost per mile to compute travel expenditures is one possible way to avoid this specification bias.

An alternative approach to including the catch-rate variable directly in the demand equation has been proposed by Brown and Sorhus (see footnote 9). It requires a two-stage estimation procedure. In the first stage, the values of selected sites are determined from estimates of the total consumer surplus obtained from a TC demand model. Ideally, a set of demand equations (one for each site) is estimated by using simultaneous-equations methods. These ordinary demand equations conditioned on prices (travel costs) for other sites are then used to calculate estimates of consumer surplus for each site. In the second stage, these estimates of consumer surplus for each site are regressed on the total number of fish caught at each site.[11] This second-stage regression provides an estimate of the marginal value of a sport-caught fish. The marginal-value estimate obtained from a linear model represents the fixed marginal value of a sport-caught fish at a typical site in the sample. Both fish-catch data and data on fishing activities from many sites are needed to apply this technique. The fish-catch data by site need not be from the same source as the data on fishing activities that are used to estimate the TC demand model. If weak complementarity between fishing trips and fish catch is assumed, one can use changes in the area under the demand curve for fishing trips to estimate the marginal value of a sport-caught fish, which is what this procedure does indirectly.

The Hedonic Travel-Cost Method

The HTC method provides estimates of the marginal value of a quality characteristic, such as the fish-catch rate, by identifying an implicit market for that characteristic. Although the marginal value of a given quality characteristic is not necessarily measured in the market for visits, as with the TC method, the implicit price of the characteristic is defined by changes in the price of a visit. Thus, even though a close relation is assumed between fishing trips and the fish-catch rate, these are not necessarily assumed to be weak complements.

A two-stage procedure is used to empirically estimate an HTC model. In the first stage, the hedonic price equation for a given zone is specified by expressing the price of a visit to each site as a function of the fixed catch rate at the site and as a function of unknown parameters describing the production technology for the sites. This first-stage equation is estimated with data on per-visit prices and catch rates across various sites visited by anglers from the zone. These data can come from a survey of a sample of anglers from the zone. The estimated hedonic price equation is then used in the second stage to specify a demand equation for visits and one for the catch rate.

The same definition as that used in a TC model for the fixed price of a visit may be used here, and it is just as important in the HTC model to obtain sufficient variability in observed prices across the sample. This means that the sites visited by anglers from a given zone must span a broad enough geographic area. In the TC model, on the other hand, this means that the residences of anglers visiting a given site must span a broad enough geographic area. The sampling methods used for each technique therefore differ.

---

[11] Frequently, data are not adequate to estimate a simultaneous-equation model, and a single-equation model for a representative site is fitted using multiple-site data. This has the serious flaw in logic of estimating the first stage under the implicit behavioral assumption that substitute sites do not exist and then, in the second stage, dropping this assumption and attempting to explain differences in estimates of consumer surplus among sites on the basis of quality of the site (fish-catch rate).

Rosen (1974) states that the hedonic price function identifies the offer function where firms are identical.[12] Because the offer function is derived, in theory, from a cost function, a theoretical form for the hedonic price equation should exist. In empirical applications of the hedonic technique, a functional form that fits the data well is usually selected. If a linear function is used, the estimated implicit characteristic prices will be constant for all anglers from a zone. Variability in implicit prices across the sample is required to estimate a demand equation for the characteristic. The only way to obtain different values for an implicit price with a linear hedonic price equation is to fit different hedonic price equations for different zones.

The demand equation for the characteristic, along with the demand equation for visits, can be derived from an explicit, functional form for the utility function, $U = U(v,z_1,y,\gamma)$. As before, v is the number of visits to a particular site and z_1 is the fixed catch per trip at that site. The symbol γ represents unknown taste parameters. In general, the demand for both v and the demand for z_1 depends on the price of v, the estimated implicit price of z_1, fixed income (M), and taste parameters (γ). Because the budget constraint is written as $M = p_v(z_1,\beta)v + y$, where $p_v(z_1,\beta)$ is the estimated hedonic price function and β denotes the estimated "technology" parameters, it follows that the estimated values of p_v, not the actual values, should be used in the demand equations. Estimated values of p_v are determined from the formula, $p_v = p_v(z_1,\beta)$. For a linear P_v equation, the coefficient of z_1 represents the implicit price of z_1. If the implicit price of z_1 is not constant for a given zone (that is, the hedonic price equation is not linear in z_1), then estimates of implicit prices are obtained from the implicit price equation, $p_1 = p_1(z_1,\beta)$.[13]

The Household-Production Method

With the HP method, as with the HTC method, demand equations for fishing trips (v) and the fish-catch rate (z_1) are derived from a utility function specified as $U = U(v_1,z_1,y,\gamma)$. In the HP model, however, the implicit price of z_1 is used directly in the budget constraint, $M = p_v(r_v,w,v,e_v,\beta)v + \pi_1(r_1,w,z_1,e_1,\beta_1)z_1 + y$, where z_1 is the total catch rather than the catch per trip, and β_v and β_1 are unknown technological parameters in each market. For a linear p_v equation, the coefficient of z_1 represents the implicit price of z_1. The implicit price functions for v and z_1 are derived from a cost function for the angler, who is both the producer and the consumer of these commodities.

The need to specify a cost function for the angler makes the basic HP method more data dependent than are the other two methods. Also, analytical difficulties can arise when both the cost function and the utility function are highly nonlinear. Because quantities of outputs (that is, commodities) as well as inputs (market goods and time)

---

[12] An offer function defines the unit prices a firm is willing to accept for various designs of a product for a fixed profit level when optimal quantities of each model are produced (Rosen 1974).

[13] A specification bias may result from using the estimated values of prices as exogenous variables in the model because the dependent variable z_1 is used to calculate these prices. An alternative procedure is to specify the characteristic demand equation in its reduced form by solving $z_1 = g_1(p(z_1,\beta), p_v(z_1,\beta),M)$ for z_1 in terms of β and M. Ideally, the complete system of equations should be fitted simultaneously, where the complete system consists of the demand equations for z_1 and v as well as the hedonic price equation for p_v and the implicit price equation for p_1. This method is not applicable, however, because observations on p_1 are not available until the hedonic price equation has been estimated.

are assumed to be endogenous, the complete system of equations includes demand equations for the commodities v and z_1 and demand equations for all inputs used to produce v and z_1. Demand equations for inputs are derived from the cost function, which will generally be defined on input prices, commodity quantities, fixed technological conditions, and unknown technological parameters.

To fit the complete system of equations, one needs data on input prices and quantities, commodity quantities, income, and indicators of technological conditions. Input prices include market prices of market goods and opportunity costs of time inputs. Price and quantity data are needed for all inputs used to produce both commodities (v and z_1). Thus, the additional data required for an HP model, as compared with the data required for a TC or an HTC model, include market prices and total input quantities (rather than just average per-trip expenditures) and data for constructing technological variables. Cross-section data will usually provide enough variability in input quantities and in technological factors that vary among anglers. Obtaining sufficient variability in market prices using cross-section data can be difficult, especially if the survey covers a relatively small geographic area.

As noted earlier both physical and biological indicators of water quality can be included in the model as technological variables. Data from several sites are needed to obtain variability in these quality factors. An HP model can be developed for a representative site from cross-sectional data for various sites.

A potential problem in gathering data to construct an HP model is the difficulty of obtaining independent data on total input quantities used by anglers during a given period. Because both the TC and HTC methods assume a constant price per visit, only data on average expenditures per visit are required to estimate these models. For an HP model, though, total input quantities are needed. It would be helpful if anglers kept a record of their expenses for every trip, so that total input usage variables could be constructed independently of the total trips variable. Also, if catch per trip is not assumed to be constant across trips, then data would have to be obtained on fish catch for all trips taken during the given period.

Constructing the Price Variable

An issue receiving attention in the literature is what types of expenditures to include in the price variable.[14] The price variable should reflect the price that a hypothetical producer might charge for a recreational experience. It should represent the recreationist's marginal willingness to pay for a recreational experience.[15] If a person's actual expenditures on any visit adequately reflect the marginal willingness to pay, it

[14] The price variable in both the TC and HTC models is defined as the sum of expenditures. Even though this is not true with HP models, what types of input prices to include in the implicit price equations must still be decided.

[15] The traditional explanation for the TC method as described by Bowes and Loomis (1980) suggests that only travel costs should be included in the price variable. There is some question about whether this definition is adequate for a study determining the benefits of quality changes at a site rather than the benefits associated with site accessibility. The use of travel costs as a proxy for an entry fee reflects only the price that a hypothetical owner could charge for access to the site—not for the complete recreational experience. For our discussion, we viewed the hypothetical owner as both a producer of a recreational experience and a transporter of it to the "market place." We tried to determine the marginal willingness to pay value at the market place.

seems reasonable to include in the price variable any expenditures beyond what the person would have otherwise spent (that is, what would have been spent in the absence of recreating). Any goods purchased beyond what would normally be consumed would presumably provide the recreationist with additional utility. This additional utility—in monetary terms—provides a measure of the benefits derived by the recreationist from the experience.

The utility-yielding components of a fishing experience include the trip itself, the sport-caught fish, and the aesthetic attributes of the site (for example, scenery and seclusion). It follows that the price variable in TC and HTC models should include the expenditures for these commodities. Expenditures made to consume the trip itself include costs of operating the vehicle (including time costs), food and lodging costs, and onsite costs (excluding costs associated with fishing activities). Food, lodging, and onsite costs are discretionary, so only those costs over and above what would normally be spent in lieu of recreating should be considered. Aesthetic attributes of a site are consumed through the process of taking the trip, so no additional expenditures are associated with these attributes. The expenditures made to consume the fish catch on a trip would include costs of fishing time, rental equipment, guide service, bait, and so on.

In both TC and HTC models, the fishing experience includes the trip itself plus the quality characteristics of the site visited (which are assumed to be exogenous). Thus, all the expenditures described above should be included in the price variable. The fixed onsite costs for consuming additional quality characteristics may be treated as quasi-entry fees. These entry fees are expected to differ across sites as quality differs. The HTC method assumes that recreationists are willing to pay additional entry fees and travel longer distances (and hence, make more travel expenditures) to obtain better quality recreational experiences. This assumption is implicitly made in the TC method because, by assuming weak complementarity, an improvement in quality shifts the demand curve for visits to the right and thereby increases the price recreationists are willing to pay for a visit.

The HP method divides the recreational experience into two commodities: the trip itself and the sport-caught fish. The price of a visit is thus based on all expenditures except those made to catch fish, which are allocated to the fish-catch commodity. In this framework, all expenditures, including travel costs, are assumed to be determined endogenously—the quantities of market goods and time used depend on fixed prices and technological conditions. Implicit price variables for visits and sport-caught fish are functions of these same variables. In the TC and HTC methods, on the other hand, the price of a visit is usually defined as the sum of actual expenditures on market goods and time. Ward (1984) shows that this procedure may lead to biased parameter estimates in demand equations for visits when discretionary costs (such as onsite expenditures and onsite time) are included in the price variable because of the endogenous nature of these types of expenditures and their likely dependence on distance traveled. Because the HP method treats all market goods and time inputs as endogenous variables, there is no reason to believe that the biases will appear in an estimated HP model.

The Aggregation Problem

One problem common to all empirical studies of consumer demand is aggregation. Normally, an empirical demand equation describes the behavior of a representative, current consumer of the commodity under the observed market conditions because price-quantity data are usually available only for current consumers rather than for all consumers, both current and potential. Thus, when the model is aggregated for current consumers, the resulting market demand curve will not account for new consumers who may begin to purchase the product as the price falls. If the model did account for all consumers, then it would generally be more price elastic than the conditional model estimated with data only for current consumers. The bias in parameter estimates from a conditional demand equation may have serious implications for measuring recreational benefits.

Brown and Mendelsohn (1983) point out that in studies of recreational demand, the use of individual observations on current consumption of a recreational resource results in a demand curve that does not accurately reflect the reduction in participation rates as distance from the site (and hence price per trip) increases. That is, this curve reflects only the decline in use by continuing consumers; it does not account for the decisions of current users to quit participating in a recreational activity as the price of a visit increases. It also does not account for the decisions of current nonusers to begin participating in the activity as the price falls. In other words, the entry and exit behavior of recreationists is not reflected along the demand curve, which results in a downward bias in the absolute value of the coefficient on the price variable. Recreational benefits are overstated with such a model.

One way to correct for the bias from not accounting for entry and exit behavior is to apply the common zonal-average method of estimating a TC demand curve. Zones around each site are defined such that individuals in the same zone face similar prices per visit. The dependent variable is defined by per-capita participation rates for each zone. Within each zone, the dependent variable is calculated by estimating the total number of visits by recreationists from the zone (based on sample observations of total trips per individual and the sampling rate) and dividing this figure by the zonal population. The independent variables are defined as zonal averages, and they are represented by the sample means for each zone.

A demand equation for visits per capita presumably describes the effect increased distance from a site has on participation rates. Because it uses zonal averages rather than individual observations of the price variable, this model also corrects for biases from any correlation between measurement errors in the dependent variable and those in the price variable.[16] One limitation is that some information is lost when individual observations are averaged (Brown and Nawas 1973, Gum and Martin 1975).

---

[16] This problem does not exist in the HP model because the implicit price of a visit is specified as a function of the fixed input prices and technology variables, none of which should be subject to measurement error.

One way to use individual observations and still account for the declining participation rate with increasing distance is to define the dependent variable for each individual observation on a per-capita basis (Brown and others 1983). How many visits each individual sample observation represents is calculated for the zone by using the same zones as in a zonal-average model; the total zonal population is then distributed across the individual observations. These allocations of zonal population are used as the denominators of the dependent variable for each individual observation. A demand model estimated with these adjusted individual observations may account for declining participation rates with distance from the site, but bias may still result from measurement errors in the price variable.

Two problems are common to both the zonal-average approach and the adjusted individual-observations approach. First, the delineation of zones is somewhat arbitrary; this is a problem if the number of zones or their sizes has any effect on the parameter estimates obtained. Second, it is theoretically more appropriate to use the total number of consumers (both current and potential) rather than total population figures as the denominators of the dependent variables; however, total population data are more empirically accessible than are data on the total number of recreationists.[17]

A demand equation for a representative consumer can be fitted by using the observations for which participation levels are zero along with the other observations in the sample. In a survey of households, many responses will come from recreationists who do not visit certain sites. Hanemann (1981) points out that the visits variable has a discrete probability mass at zero and is highly skewed with a long right tail. For this type of probability distribution, Hanemann (1981) suggests that the recreationist's decision process be modeled as a two-step procedure. The first stage is the qualitative choice of whether or not to participate in a particular recreational activity, and the second stage is the quantitative decision of how many recreational trips to make when the decision to participate has been made. The product of the probability of participation (estimated in the first stage) and the conditional rate of participation (estimated in the second stage) gives the expected participation for a representative consumer.

Neither the zonal-average method nor the adjusted individual-observations method directly models the participation decision (Hanemann's first-stage qualitative decision). Rather, they each attempt to derive the true market demand curve by accounting for differences in participation rates along the demand curve. McConnell suggested that rather than fit a per-capita demand equation, one could use a two-stage procedure, similar to Hanemann's procedure, that would more explicitly model the participation decision.[18] The first-stage model would specify the participation rate for

[17] One way to estimate the total number of recreationists for each zone is to estimate the proportion of the total population in the zone closest to the given site that will visit the site. If the residents of the closest zone face a near-zero price per visit, this proportion should give a good estimate of the percentage of a population that would visit the site if the price were to fall to zero. This percentage estimate can be used to adjust each zone's population to a total-recreationist basis.

[18] Personal communication, Ted McConnell, University of Maryland, Room 2200, Symons Hall, College Park, MD 20742.

each zone as a function of distance. The second-stage model would specify the conditional number of visits for each individual recreationist as a function of distance or price and any other demand determinants. The predicted conditional number of visits could be multiplied by the predicted participation rate for the appropriate zone (which serves as a probability-of-participation variable) to predict the individual's expected participation. (A hypothetical example of this approach is presented in chapter 5, part I.) Although this two-stage approach models the participation decision in a more explicit manner than does the per-capita demand model, the approach does not relate both stages of the decision process to a common utility-maximization problem. As no theoretical basis exists for the first-stage model, the choice of a functional form appears to be arbitrary.

More work must be done to develop unified utility-theoretic models explicitly allowing both discrete and continuous consumer choices. Hanemann (1984) developed discrete and continuous-choice models that he uses when the consumer chooses among various goods differing in price and quality. These models are based on random-utility theory, and the discrete- and continuous-choice models are each derived from a single utility-maximization problem. In these models, discrete choices can be specified using logit, generalized logit, or probit models, depending on the probability distribution used for the random disturbances of the utility function. More similar research is needed to develop a utility-theoretic foundation to explicitly account for the qualitative and quantitative dimensions of recreational behavior.

Policy Considerations

The three methods were evaluated by the kinds of policy questions each can handle. In particular, the usefulness of each model was judged on the quality variables that can be included in the model, which suggested the policy-induced quality changes each model can be used to evaluate and the data needed to apply each model.

Both the TC and HTC models are restricted to evaluating quality changes perceived by recreationists. Quality variables only enter these models through the utility function, and these quality factors directly influence recreationists' choice of site and level of participation at a given site. Quality variables should therefore be defined by the recreationist's subjective evaluation of quality.

The main advantage the HTC method has over the TC method is that an implicit market is defined for each quality characteristic, so that a weakly complementary relationship between each quality characteristic and the visits variable is not necessary to evaluate the benefits of quality changes. The scope of the HTC method for evaluating the effects of policy-induced quality changes is thus somewhat broader than that of the TC method. Another advantage of the HTC method for sport fishing is that a fish catch-rate variable can be included directly in the model because it is treated as an endogenous choice variable. As mentioned earlier, including a catch-rate variable in a TC model can lead to biased parameter estimates. By use of the two-stage procedure of Brown and Sorhus (see footnote 9), the marginal value of a sport-caught fish can be determined from fish-catch data, by site, that need not come from the same source as the data on fishing trips.

Estimates of the marginal value of a sport-caught fish from either a TC or an HTC model may be useful for evaluating the benefits of exogenous changes in fish catch; for example, recreational benefits of an increase in fish stocks or an improvement in habitat and water quality can be determined. Of course, prior knowledge of the effects on fish catch of changes in fish stocks or habitat and water quality is necessary. The effects of these changes can be specified directly in the HP model. Without additional information beyond that provided by an empirical HP model for sport fishing, the benefits of increases in fish stocks or of improvements in habitat or water quality can be evaluated. The HP model provides estimates of marginal values for any exogenous quality factors included as technology variables in the model. Using policy-related variables is desirable in constructing a model for evaluating policy changes.

Marginal values can also be determined for any exogenous quality characteristics included as variables in the utility function in the HP model (as in the TC model). Because fish catch is treated as an endogenous variable in this model, the model does not provide estimates of the marginal value of a sport-caught fish, but it does give an estimate of the average value. Average values are not always appropriate for determining the effects of marginal changes in quantities of a commodity, so the HP model may not be useful for evaluating the effects of changes in fish catch caused by changes in quality factors not included in the model as technology variables. When the relevant policy-related variables are included in the model, the HP model has definite advantages over both the TC and HTC models in the evaluation of policy-induced quality changes.

Summary

We have described the theoretical foundations for three recreation-valuation methods. All three methods can be derived from a constrained utility-maximization problem, and nonmarket values for recreational commodities are inferred from hypothesized relations between these commodities and various groups of market goods. The three methods differ primarily in (1) the decisionmaking processes used to describe the behavior of recreationists and in (2) the role recreationists have in determining the quality of a recreational experience. These distinguishing factors have implications for how each method can be used to measure benefits to recreationists from changes in quality.

The single-site TC model assumes that the recreationist decides only how often to visit the recreational site (or a representative site when multiple-site data are used). Although the recreationist may consider the quality attributes of the site, those attributes are assumed to be completely exogenous to making the decision. By assuming a weakly complementary relation between a quality attribute and the recreationist's participation at a site, one can determine the nonmarket value of the attribute in terms of benefits derived from the recreational experience.

The HTC method sees the recreationist selecting a bundle of quality characteristics that the recreationist would like the recreational experience to contain. After this decision is made, the recreationist decides how many times to visit the site offering that bundle of characteristics. Because each type of quality characteristic is treated as an endogenous choice variable in the HTC model, an implicit market is defined for each characteristic. The nonmarket value of a characteristic can thus be determined by measuring benefits in the market for that characteristic. The implicit price of a characteristic is defined by the additional expenditures a recreationist is willing to make to visit a site offering one more unit of the characteristic. The bundle of characteristics provided at each site is assumed to be fixed.

The HP method drops this assumption for certain types of quality characteristics, such as the fishing-success rate. For certain recreational commodities, including the fishing-success rate and the level of participation at a recreational site, the recreationist is viewed as both a producer and a consumer. Implicit commodity prices are defined by the minimum cost necessary to produce one more unit of the commodity. Included are expenditures on market goods and the opportunity costs of time used in the production process. Nonmarket values of an endogenous quality characteristic (such as the fishing-success rate) may be measured in the market for that characteristic, which is represented by an endogenous supply and demand for each site. With this technique, nonmarket values may also be determined for exogenous quality factors influencing the supply of endogenous characteristics.

Although the TC method makes the most restrictive assumptions about the recreationist's decisionmaking, it has the advantage of being less data dependent than the other two methods. This method usually involves fitting a single demand equation for the recreational activity. Exogenous quality variables can be included in this demand equation. Variability in quality can be found in data obtained for several recreational sites. Variability in the price of a recreational experience can normally be obtained with data for recreationists who traveled different distances to visit each site.

The development of an HTC model requires that the given geographic area where different sites are located be divided into several zones. The recreationists living in each zone must visit several different sites at various distances from the zone that have various quality attributes. Fitting the hedonic price equation for each zone requires that the distance traveled to each site be significantly correlated with the quality attributes of each site. The hedonic price equation fit for a given zone provides a set of implicit prices for the quality characteristics. With implicit price data for several different zones, a demand equation for each characteristic can be fit.

The HP method has the most extensive data requirements of the three methods. Price data for inputs as well as quantity data on both inputs and commodities are required to fit the complete system of input and commodity demand equations. Quantities and implicit prices of commodities, including endogenous quality characteristics, typically vary among recreationists. If exogenous quality variables are included in the model, then data for multiple sites will be required because these data will not differ among recreationists for a given site. Objective quality data can be used to define these exogenous quality variables.

To include any quality variables in either the TC or HTC model, on the other hand, requires data on recreationists' subjective evaluations of quality attributes at various sites. The same is true of exogenous quality variables included in the utility function of an HP model. These quality variables are assumed to directly influence a recreationist's decision to participate. Recreationists most likely base their decisions on how they personally rate the quality of a site.

To use the TC and HTC models in policy evaluation, the relationships between policy-related variables and the subjective quality variables included in the models must first be specified. The HP model thus has a definite advantage for policy evaluation over these other two models when policy-related variables are included in the model as determinants of the supply of commodities. In certain circumstances, the extra effort to construct an empirical HP model would therefore be worthwhile. The HTC method seems to have an advantage over the TC method in evaluating the benefits of quality changes because the condition of weak complementarity does not have to be met with the HTC method.

The availability of data and the types of quality variables to include in a model influence the decision on which method to use in a given situation. The underlying assumptions of each approach should be given careful consideration, especially those on the recreationist's role in determining the quality of a recreational experience. The quality characteristics of interest not only influence the selection of a model but also affect the definitions of price variables.

We briefly discussed the problems of defining prices of recreational commodities and of accounting for both the qualitative and quantitative dimensions of recreational behavior. Further research is suggested on relating discrete- and continuous-choice models to a common, utility-maximization problem.

Literature Cited

Bockstael, Nancy E.; McConnell, Kenneth E. 1981. Theory and estimation of the household production function for wildlife recreation. Journal of Environmental Economics and Management. 8: 199-214.

Bockstael, Nancy E.; McConnell, Kenneth E. 1983. Welfare measurement in the household production framework. American Economic Review. 73(4): 806-814.

Bowes, Michael D.; Loomis, John B. 1980. A note on the use of travel cost models with unequal zonal populations. Land Economics. November; 56: 465-470.

Brown, Gardner; Mendelsohn, Robert. 1984. The hedonic travel cost method. Review of Economics and Statistics. 66(3): 427-433.

Brown, William G.; Nawas, Farid. 1973. Impact of aggregation on the estimation of outdoor recreation demand equations. American Journal of Agricultural Economics. 55(2): 246-249.

Brown, William G.; Sorhus, Colin; Chou-Yang, Bih-lian; Richards, Jack A. 1983. Using individual observations to estimate recreation demand functions: a caution. American Journal of Agricultural Economics. 65(1): 154-157.

Deaton, Agnus; Muellbauer, John. 1980. Economics and consumer behavior. London: Cambridge University Press. 450 p.

Gum, Russell L.; Martin, William E. 1975. Problems and solutions in estimating the demand for and value of rural outdoor recreation. American Journal of Agricultural Economics 57(4): 558-566.

Hammack, Judd; Brown, Gardner Mallard, Jr. 1974. Waterfowl and wetlands: toward bioeconomic analysis. Baltimore, MD: Resources for the Future. 95 p.

Hanemann, W. Michael. 1981. Water quality and the demand for recreation. Working pap. 164. [Berkeley, CA]: California Agricultural Experiment Station. Giannini Foundation of Agricultural Economics, University of California. 43 p.

Hannemann, W. Michael. 1984. Discrete/continuous choice models of consumer demand. Econometrica. 52(3): 541-561.

Muellbauer, John. 1974. Household production theory, quality, and the 'hedonic technique.' The American Economic Review. 64(6): 977-994.

Rosen, Sherwin. 1974. Hedonic prices and implicit markets: product differentiation in pure competition. Journal of Political Economy. January/February; 82: 34-55.

Smith, V. Kerry; Desvousges, William H.; McGivney, Matthew P. 1983. Estimating water quality benefits: an econometric analysis. Southern Economic Journal. 50(2): 422-437.

Strong, Elizabeth J. 1983. Measuring benefits of outdoor recreation services: an application of the household production function approach to the Oregon steelhead sport fishery. Corvallis, OR: Oregon State University. 160 p. M.S. thesis.

Ward, Frank A. 1984. Specification considerations for the price variable in travel cost demand models. Land Economics. 60(3): 301-305.

Chapter 3: Empirical Results From the Travel-Cost Model: Zonal-Average and Adjusted Individual-Observation Versions

William G. Brown and Ching-Kai Hsiao[1]

In this chapter, we present empirical estimates of travel-cost models for the values of salmon and steelhead fishing in Oregon. The values of salmon and steelhead catch were estimated based on estimates of consumer surplus from the travel-cost models and estimates of fish catch from the Oregon Department of Fish and Wildlife.

Theoretical Relationships Between Angler Benefits and Fish Catch

The estimation of values of salmon and steelhead catch can be greatly simplified if a linearly homogeneous relationship exists between consumer surplus to anglers and fish catch. A question can justifiably be raised, however, on whether a linearly homogeneous relationship between consumer surplus and fish catch per river is consistent with economic theory and utility maximization. Although a complete and comprehensive treatment of this question was beyond the scope and intent of this study,

[1] WILLIAM G. BROWN is professor, Oregon State University, Department of Agricultural and Resource Economics, Corvallis, OR 97331. CHING-KAI HSIAO was research assistant, Oregon State University, Department of Agricultural and Resource Economics, Corvallis, OR 97331; he is currently employed by National Chung-Hsing University, Department of Agricultural Economics, Taichung, Republic of China.

a brief analysis indicated that under fairly plausible conditions, a linearly homogeneous relationship can be produced via economic theory. Two main aspects of the necessary conditions are (1) the form of the utility function, if such exists, that will cause consumer surplus to vary proportionally to fish catch; and (2) the kind of budget constraint that will, in combination with the utility function, result in a particular functional form of the demand for fishing days or trips. Although other functional forms for utility can give a similar result, one of the simpler forms is:

$$u = q_2^{\beta_2} q_3^{\beta_3} \tag{1}$$

where $b_2 = b_0 q_1^{b_1} < 1.0$, b_0 and $b_1 > 0$, $\beta_3 = 1 - \beta_2$, q_1 is fish catch of angler, q_2 is quantity of fishing trips, and q_3 is all other consumption goods. This formulation also assumes that catch per unit of effort is not subject to the angler's control,[2] but that the angler has good information about the ratio of catch to effort for given rivers.

By maximizing (1) subject to the usual linear budget constraint $p_2 q_2 + p_3 q_3 = x$, the Marshallian demand function can be solved for:

$$q_2 = \frac{b_0 q_1^{b_1} x^{-1}}{P_2} \tag{2}$$

According to (2), the number of fishing trips is a strictly increasing function of the fish catch expected by the angler. The demand relation in (2) implies that fishing trips would not be taken if the angler did not think the probability of catching fish was greater than zero. At any rate, the consumer surplus from (2) can be estimated only if an upper bound is set for p_2, say $p_2 = TC_{max}$, where TC_{max} is usually set equal to the largest of the observed travel costs. The consumer surplus is directly proportional to fish catch if and only if $b_1 = 1.0$. This same result was also deduced from (1) for the semilog form of the demand function to be used later, but it required a nonlinear budget constraint that was difficult to justify on economic grounds. (Details are available from the authors.)

Estimated Zonal-Average Travel-Cost Demand and Benefits

Freshwater Salmon Angling

Estimates of demand and benefits for freshwater salmon by Sorhus (1980) used traditional zonal-average travel-cost models and were based on the unedited data coded from questionnaires. Contract deadlines with the Pacific Northwest Regional Commission, which funded a 1977 survey of Oregon anglers and the first estimates of demand and benefits, did not permit added checking of the travel-cost data by going back to the original questionnaires.

For this analysis, the data were edited, entirely new distance zones were constructed, and travel-cost variables corresponding to these distance zones were computed based on careful examination of the original questionnaires. By reworking the angling data for freshwater salmon, enough observations were obtained to construct

[2] An excellent treatment of theoretical considerations in wildlife recreation, including the effect of assuming an endogenous versus an exogenous catch rate, is presented by Bockstael and McConnell (1981).

distance zones for nine rivers, as compared to only eight in the travel-cost analysis by Sorhus. Among the various zonal travel-cost models fitted, the following semilog form was judged most appropriate:

$$\ln (TRPSCAP)_i = -1.425 - \underset{(-9.35)}{0.05189}\ RTC_i + \underset{(2.47)}{0.0001552}\ S\text{-}SEQP_i$$

$$- \underset{(-6.33)}{1.102}\ X_1 - \underset{(-3.81)}{0.9204}\ X_2 - \underset{(-3.41)}{1.651}\ X_3 \quad n = 37 \quad R^2 = 0.815 \ . \quad (3)$$

In this chapter, R^2 and r^2 denote the proportion of variation in the mean-corrected dependent variable explained by the regression. Numbers in parentheses are t-statistics for the coefficients.

In (3), $TRPSCAP_i$ denotes average salmon-fishing trips per capita from distance zone i to the specified river. RTC_i denotes revised travel cost to zone i with travel time assumed to be worth one-third of the wage rate.[3] (The hourly wage rate for each zonal observation was computed by dividing the average yearly income by 2,000.) The symbol $S\text{-}SEQP_i$ is the average replacement value per respondent in zone i of fishing and related equipment used for salmon and steelhead angling; X_1 is a dummy variable that took the value of one if the respondents of zone i resided in Multnomah, Washington, or Clackamas County and took the value of zero otherwise; X_2 is a dummy variable that took the value of one if the river was the Rogue River, otherwise X_2 was equal to zero; and X_3 is a dummy variable that took the value of one if the river was the Coos River and was otherwise equal to zero.

Thirty-seven completely new distance zones were constructed and the variables recomputed to fit equation (3). (Sorhus's earlier model was fitted to only 25 zonal observations.) Some observations were either deleted or corrected when errors in coding of the original data were detected. In addition, enough observations were found from the questionnaires to add the Wilson River to the travel-cost model. Despite all these changes, the crucial travel-cost coefficient in (3) remained surprisingly close to the original estimate by Sorhus.

Angler benefits related to fish catch—Our first research efforts in incorporating fish catch directly into the angler demand model for fishing trips were wasted. Our idea was that fishing success acts as a demand shifter with a high fish catch for a given river expected to increase the amount of fishing on that river. But our attempts to augment travel-cost demand models with fish-catch data resulted only in serious problems with specification and estimation. We have not presented details here, but instead have outlined another procedure developed by Samples and Bishop (1985) that gives much better results.

Our version of the Samples-Bishop procedure was to estimate the travel-cost-based demand function for the various rivers in one equation. From this equation, consumer surplus was estimated for each river. Then, the total consumer surplus for each river was regressed against the corresponding fish catch for that river. The procedure is illustrated for freshwater sport salmon and steelhead fishing in Oregon.

---

[3] Travel cost per trip includes the estimated variable cost per mile of operating a vehicle times the miles driven plus food and lodging costs incurred while traveling. Costs incurred at the destination are not included.

Table 1—Zonal-average travel-cost estimates of consumer surplus for Oregon freshwater salmon sport anglers, 1977

River	Estimated catch of salmon[a]	Traditional estimate of consumer surplus per river[b]	Gum-Martin[c] estimate of consumer surplus per river[b]	Distance from Portland[d]
		Dollars		*Miles*
Alsea	2,290	399,900	193,800	104
Clackamas	2,149	487,900	161,900	18
Columbia	13,172	1,316,600	1,480,300	10
Coos	573	45,200	45,200	212
Deschutes	3,833	71,400	87,400	65
Rogue	8,864	236,600	247,100	245
Umpqua	4,570	477,100	708,700	172
Willamette	14,222	1,720,400	1,638,100	10
Wilson	4,692	161,200	160,700	38
Total	54,365	4,916,300	4,723,200	

[a] Reported by Oregon Department of Fish and Wildlife.

[b] Estimated from equation (3) (see text).

[c] Gum and Martin 1975.

[d] All distances were assumed to be a minimum of 10 miles.

Relation of estimated angler benefits to salmon sport catch—Estimated net economic benefits and fish catch of Oregon freshwater salmon anglers are shown in table 1 for the nine rivers included in equation (3). For the semilog functional form of (3), consumer surplus for the *ith* distance zone is equal to the predicted participation of zone i divided by the travel-cost coefficient. To see this clearly, write the travel-cost demand function as $q_i = a_i e^{bx_i}$, where q_i is the predicted per capita participation rate of zone i and x_i is the travel cost. The constant a_i is assumed to include the effect of any other variables included in the travel-cost equation.

Show the observed travel cost of zone i by x_i^0. Then $q_i^0 = a_i e^{Gx_i^0}$, and the consumer surplus is by definition the integral of the q-function as x_i ranges from x_i^0 to ∞. That is:

$$CS_i = \int_{x_i^0}^{\infty} a_i e^{Gx_i}\, dx_i = \frac{a_i}{b} e^{Gx_i} \Big|_{x_i^0}^{\infty} = -\frac{a_i e^{Gx_i}}{b} = -\frac{q_i^0}{b} ,$$

and $CS_i = -q_i^0/b$, as indicated.

The traditional estimate of consumer surplus (table 1) was computed by dividing the predicted trips per capita for each distance zone by the travel-cost coefficient from equation (3), multiplying by the zone population, and summing the zonal consumer surpluses for a specified river. In this way, consumer surplus to Oregon freshwater salmon anglers was computed for each of the nine rivers. These estimated angler benefits per river are given in table 1.

By regressing the traditional estimates of consumer surplus for the nine rivers in table 1 as a linear function of fish catch per river ($CTCH_j$), we obtained:

$$CS_j = \underset{(-0.32)}{-58{,}981} + \underset{(4.18)}{100.20}\ CTCH_j \quad n = 9 \quad r^2 = 0.714\ . \tag{4}$$

The constant term in (4) is far from being statistically significant because the absolute value of t is less than one. Because using the linearly homogeneous form of (4) offers some advantages, to be discussed later, the constant term was deleted, yielding:

$$CS_j = \underset{(6.84)}{94.05}\ CTCH_j \quad n = 9 \quad r^2 = 0.710\ . \tag{5}$$

According to (5), the marginal value of salmon catch is around $94 per fish; however, as only the nine most important salmon fishing rivers are represented in table 1, some adjustments are needed. Also, the degree of homogeneity of the consumer surplus-fish catch relationship might not be one as assumed by (5). To test the hypothesis that the degree of homogeneity was different from one, (6) was fitted:

$$\ln(CS)_j = \underset{(2.05)}{5.477} + \underset{(2.69)}{0.8594}\ CTCH_j \quad n = 9 \quad r^2 = 0.562\ . \tag{6}$$

By computing t = (0.8594 - 1.0)/0.3191 = -0.44, we find that this small value of t falls far short of significance. Therefore, based on the traditional estimate of consumer surplus and fish-catch data of table 1, the hypothesis that the salmon anglers' consumer surplus is a linearly homogeneous function of fish catch cannot be rejected.

One important aspect of the preceding analysis is that the estimated fish-catch data in table 1 are independent of the data used to estimate the consumer surplus in table 1. Salmon sport-catch data are collected each year by the Oregon Department of Fish and Wildlife and are based on the return of salmon-steelhead punch cards and other information. The consumer-surplus analysis was based on our own survey of about 1.5 percent of Oregon anglers (described earlier).

If net economic benefits to sport salmon anglers are approximately a linearly homogeneous function of salmon catch, then estimating benefits from increasing salmon runs and angler catch is greatly simplified. For example, if a new salmon hatchery on the Coos River could increase the runs of salmon, and if salmon catch were increased by 3,000 fish per year, then the projected increase in benefits would be about $94.05(3,000) \doteq \$282{,}000$ per year based on equation (5).

A second method was also used to compute the consumer surplus in the last column of table 1, which was based on the innovative research of Gum and Martin (1975). By employing their approach, we used the observed number of fishing trips per capita, rather than the predicted number of trips per capita, as the basis for

computing consumer surplus.[4] The Gum-Martin procedure has some advantages over the more traditional approach, especially for our purpose of relating net economic benefits to catch, because their procedure is far less sensitive to possible errors in the demand model specification that might cause the angler's use of some rivers to be overestimated or underestimated.

By regressing the Gum-Martin estimate of consumer surplus in table 1 as a linear function of fish catch, we obtained:

$$GMCS_j = \underset{(-0.89)}{-148{,}728} + \underset{(5.09)}{111.50}\ CTCH_j \qquad n = 9 \qquad r^2 = 0.787\ . \tag{7}$$

Again, as for equation (4), the constant term in (7) is not statistically significant with a t-value of less than one. Because the linearly homogeneous form of (7) has advantages, the constant term was deleted, yielding:

$$GMCS_j = \underset{(7.29)}{96.01}\ CTCH_j \qquad n = 9 \qquad r^2 = 0.763\ . \tag{8}$$

The hypothesis that the degree of homogeneity of the relationship between consumer surplus and fish catch was not equal to one was tested by fitting:

$$\ln (GMCS)_j = \underset{(1.88)}{4.0326} + \underset{(3.98)}{1.0178}\ \ln (CTCH)_j \qquad n = 9 \qquad r^2 = 0.694\ . \tag{9}$$

Computing t = (1.0178 - 1.0)/0.2556 = 0.07, we find that this small value of t is far from being statistically significant. Consequently, the hypothesis that the salmon anglers' net economic benefits are a linearly homogeneous function of fish catch cannot be rejected based on the data in table 1.

The estimated fish-catch data in table 1 are independent of the data used to estimate the consumer surplus in table 1; this makes the estimated linearly homogeneous relationship between estimated consumer surplus and fish catch more impressive. The relationship between estimated consumer surplus per river for steelhead anglers and the steelhead catch per river should be examined before we discuss the implications of the estimated values of sport-caught salmon.

---

[4] Consumer surplus was traditionally computed for each zonal observation by calculating the area under the demand curve predicted for that zone and the average travel cost observed for that zone. Essentially, the Gum-Martin approach shifts the predicted demand for the observation up or down so that the demand curve passes exactly through the observed quantity-travel cost point. (Although Gum and Martin developed their method for use with individual observations, it is also easily used for zonal-average observations, as in this paper.) As Ward notes (1981), one advantage of the Gum-Martin procedure is that it always yields a nonnegative consumer surplus, in contrast to the traditional procedure where consumer surplus must be set equal to zero for negative predicted quantities.

Steelhead Angling

A unique set of distance zones was constructed around each of 21 Oregon rivers fished by steelhead anglers. There were 81 zones with an average of about four anglers per zone who actually fished in the quarter that they received a questionnaire for. The following semilog demand equation was estimated by ordinary least squares:

$$\ln (TRPSCAP)_i = \underset{(-12.35)}{-2.167} - \underset{(-7.42)}{0.0365}\, RTC_i - \underset{(-4.48)}{1.043}\, X_1 - \underset{(-2.28)}{1.600}\, X_2 + \underset{(2.66)}{1.109}\, X_3 + \underset{(2.76)}{1.025}\, X_4 + \underset{(1.91)}{0.8117}\, X_5 \quad n = 81 \quad R^2 = 0.569 . \tag{10}$$

Variables in (10) are defined as they were for equation (3). Again, X_1 is a dummy variable that took the value of one if respondents of zone i resided in Multnomah, Washington, or Clackamas County and took the value of zero otherwise.

One difference between the estimated demand for steelhead fishing in (10) and for freshwater sport salmon angling in equation (3) is that the fishing-equipment variable did not come close to being statistically significant in the steelhead fishing demand equation; this emphasized the possible differences between salmon and steelhead angling. Four of the rivers had significant dummy variables, X_2, X_3, X_4, and X_5, representing the Chetco, Deschutes, Nestucca, and Umpqua Rivers, respectively. (Without these dummy variables, per capita fishing effort was consistently underestimated or overestimated on these rivers.)

Although some omitted-variable specification bias can occur by not including some of the income or equipment-related variables in (10), the results of fitting other regression equations that included these variables indicated that the squared error loss for the important travel-cost variable would likely be increased by including these other variables. Because estimated net economic benefits are directly related to the travel-cost coefficient, equation (10) was judged the appropriate equation for estimating net economic benefits.

By following the same procedure outlined for freshwater salmon angling, we computed net economic benefits for each distance zone of each river and summed to obtain the estimated benefits for each of the 21 rivers, (table 2).[5] By regressing the Gum-Martin consumer surplus per river as a simple linear function of steelhead catch, the following ordinary least squares estimate was obtained:

$$GMCS_j = \underset{(0.85)}{123{,}216} + \underset{(4.38)}{93.62}\, CTCH_j \quad n = 21 \quad r^2 = 0.503 . \tag{11}$$

[5] The Gum-Martin approach to estimating consumer surplus should be less sensitive than the traditional consumer surplus to possible specification errors that can cause the consumer surplus for some rivers to be overestimated or underestimated. Consequently, only the Gum-Martin consumer surplus is given in table 2. The traditional consumer surplus presented by Sorhus (1980) has a similar relationship to fish catch, but those equations are not included.

Table 2—Zonal-average travel-cost estimates of consumer surplus for Oregon steelhead sport anglers

River	Estimated catch of steelhead[a]	Total consumer surplus per river[b]
		Dollars
Alsea	6,651	783,800
Chetco	2,756	39,200
Clackamas	5,868	1,214,800
Columbia	3,810	412,800
Coquille	2,521	282,100
Coos	1,541	58,200
Deschutes	9,663	847,500
Hood	2,679	146,400
John Day	2,252	100,400
Nehalem	3,325	150,300
Nestucca	13,465	1,555,700
Rogue and Illinois	12,704	1,150,700
Salmon	2,533	334,100
Sandy	7,445	650,100
Santiam	6,486	1,270,600
Siletz	11,619	321,700
Siuslaw	2,145	512,100
Trask	3,086	627,000
Umpqua	9,213	1,632,200
Willamette	2,349	545,600
Wilson	7,730	1,171,600
Total	119,841	13,806,900

[a] Reported by Oregon Department of Fish and Wildlife for 1977.

[b] Estimated from equation (10) and using the method of Gum and Martin (1975).

Given the low t-value of 0.85 for the constant term and the advantages of a linearly homogeneous functional relationship, the constant term was deleted and (12) was obtained:

$$GMCS_j = \underset{(9.42)}{108.81}\ CTCH_j \qquad n = 21 \qquad r^2 = 0.484\ . \tag{12}$$

To test if the degree of homogeneity was significantly different from one, the double-log equivalent of (11) was fitted to obtain:

$$\ln (GMCS)_j = \underset{(1.57)}{3.4047} + \underset{(4.44)}{1.1356}\ \ln (CTCH)_j \qquad n = 21 \qquad r^2 = 0.509\ . \tag{13}$$

Testing the hypothesis that the coefficient for ln $CTCH_j$ in (13) was equal to one, the value of t was:

$$t = \frac{1.136 - 1.0}{0.2559} = 0.53 .$$

Because this t-value was not statistically significant, even at the 50-percent probability level, the hypothesis of a linearly homogeneous relationship between angler benefits and steelhead catch cannot be rejected.

Ocean Salmon Angling

The procedure used to fit the travel-cost demand model for ocean salmon fishing was essentially the same as for freshwater salmon and steelhead except distance zones were constructed so that respondents within zones had fairly uniform distances to the ocean. There were 21 distance zones with an average of over eight respondents per zone (Sorhus 1980, p. 114). The following equation was the most satisfactory of several that were fitted:

$$\ln (TRPSCAP)_i = -2.508 - \underset{(-5.70)}{0.01875}\ TRVCST_i + \underset{(1.21)}{0.00006931}\ INC_i - \underset{(-1.22)}{0.1224 \times 10^{-8}}\ INCSQ_i \quad n = 21 \quad R^2 = 0.661 . \tag{14}$$

In (14), INC_i is the average income per respondent for zone i, and $INCSQ_i$ is INC_i squared. The other symbols in (14) are the same as defined in earlier equations, except that no travel-time cost was included in $TRVCST_i$.

The consumer surplus per capita was computed for each zone and then multiplied by the zone's population to obtain the total consumer surplus for each zone. Summing the traditional estimate of consumer surplus for the 21 zones gave a total estimated net economic benefit of about $13.1 million. The Gum-Martin estimate of consumer surplus was slightly higher at $13.46 million. Dividing the Gum-Martin estimate by the ocean salmon catch for 1977 yielded $13.46 million ÷ 260,683 ≐ $52 per fish. Equation (14) can be criticized for not making efficient use of the data because an average of over eight observations per zone yielded only 21 zonal observations. Efficiency might have been increased by grouping ports by county and constructing distance zones around these ports in the way distance zones were constructed around the individual rivers. We constructed distance zones around six coastal counties: Clatsop, Tillamook, Lincoln, Lane and Douglas combined, Coos, and Curry. The most suitable travel-cost model was:

$$\ln (TRPSCAP)_i = -2.043 - \underset{(-7.10)}{0.01843}\ RTC_i \quad n = 47 \quad R^2 = 0.528 . \tag{15}$$

RTC_i is the revised travel cost with travel time valued at one-third the wage rate. The Gum-Martin estimate of consumer surplus was $13.726 million. Dividing the Gum-Martin estimate of consumer surplus by the ocean salmon catch gave $13.726 million ÷ 260,683 ≐ $53 per fish. An average Gum-Martin consumer surplus per trip of about $54 was estimated from equation (15) as compared to the $53 per trip estimated by equation (14).

Effect of Other Factors on Estimated Benefits Per Fish

Many things—such as scenery, access, and congestion—can cause consumer surplus per fish to vary from one river to another. Proximity to the Portland metropolitan area might be an important factor affecting angler benefits; we hypothesized that salmon or steelhead rivers close to Portland would have higher demands and correspondingly higher estimates of consumer surplus per fish caught. We tested the hypothesis by measuring the approximate minimum distance of each river to the Portland metropolitan area; all distances were assumed to be at least 10 miles. Distances from Portland are shown in table 1.

Various models for the consumer surplus per river, as a function of salmon catch and distance from Portland, were fitted. The consumer surplus per river was regressed against salmon catch per river and salmon catch per river times the distance from Portland (DP) in miles:

$$CS_j = \underset{(9.21)}{112.01\ CTCH_j} - \underset{(-2.73)}{0.3224\ (CTCH \cdot DP)_j} \quad n = 9 \quad R^2 = 0.860\ . \qquad (16)$$

From (16), we can infer that each additional mile from the Portland metropolitan area reduces the average value per salmon by about 32 cents. This estimate of the effect of distance from Portland actually seems too high because a distance of 200 miles reduces the value per fish to less than one-half the value of a fish caught near Portland. One reason the effect of distance may be overestimated is that some of the southern Oregon rivers, such as the Rogue, almost certainly have many anglers from California. Estimating the travel-cost model when a few recreationists from great distances are included in the analysis is quite difficult. Out-of-State anglers were therefore not included in the estimation of travel-cost equations, and no estimate of the out-of-State anglers' consumer surplus is included in tables 1 and 2. If a significantly higher percentage of out-of-State anglers were fishing the Rogue and some of the other southern Oregon rivers, equation (16) would overstate the negative effect of distance from Portland on the average value per fish. Further research is obviously needed to see if reasonably accurate estimates of out-of-State anglers versus Oregon anglers can be obtained for the rivers in tables 1 and 2.

Consumer surplus per river from table 1 (Gum-Martin estimate) was also regressed against the estimated salmon catch per river and the interaction term, which was salmon caught per river times distance from Portland:

$$GMCS_j = \underset{(9.30)}{112.55\ CTCH_j} - \underset{(-2.53)}{0.2969\ (CTCH \cdot DP)_j} \quad n = 9 \quad R^2 = 0.876\ . \qquad (17)$$

Results from (17) are similar to those from (16) with an implied reduction in value per fish of about 30 cents for each additional mile from the Portland area. The coefficient for the distance variable, DP, by itself was not statistically significant for either the traditional or the Gum-Martin estimate of consumer surplus, although the DP coefficient did have the expected negative sign.

A more realistic estimate of the effect of DP was obtained from the steelhead data, possibly because of the greater number of observations available for the steelhead streams—21 vs. only 9 for salmon. At any rate, one of the better fitting linear models was:

$$GMCS_j = \underset{(6.39)}{126.6\ CTCH_j} - \underset{(-1.10)}{0.1637\ (CTCH \cdot DP)_j} \quad n = 21 \quad R^2 = 0.515\ . \qquad (18)$$

According to (18), each additional mile from Portland reduces the value of a fish by about 16 cents, or by $16 for each 100 miles. Thus, consumer surplus per fish is estimated from (18) to be only about $94 per steelhead at 200 miles from Portland as compared to about $125 per steelhead at only 10 miles from Portland. This estimate has to be considered very rough, given that the consumer surplus for fishing along southern Oregon streams may be underestimated because of a larger percentage of California anglers. Furthermore, some anglers prefer chinook salmon over coho, and total salmon catch cannot reflect such preferences. In addition, although the anglers in our analysis fished primarily for either salmon or steelhead, a stream that offered a higher probability of catching both might have been preferred.

We examined creel-census data on catch and effort for the Deschutes and the Alsea Rivers. The creel census provided more accurate estimates of catch than did the catch data in tables 1 and 2, which were based primarily on salmon and steelhead tag returns. The creel census also provided much more accurate data on total fishing effort than did the data collected by Sorhus and others (1981), which provide the basis for the consumer surplus estimated in tables 1 and 2. The shortcomings of our data are illustrated by creel-census data for the Deschutes River. Creel-census data indicate that the 1977 catch of adult spring and fall chinook salmon was 1,459 adults and 915 jacks; however, the catch estimated from salmon and steelhead tags was 3,383 (from table 1). In addition, salmon fishing trips to the Deschutes were apparently underestimated by our relatively small 1977 survey of Oregon anglers; the result was too small an estimate of consumer surplus (table 1). Once we had the 1977 creel-census data for the Deschutes, a more realistic estimate of consumer surplus per fish could clearly be computed for the Deschutes by dividing the Gum-Martin estimate of consumer surplus (table 1) by an "adult salmon equivalent" catch based on census data. (If three jacks were equivalent to one adult salmon, then an adult-equivalent catch would be about 1,764.)

A somewhat more accurate estimate of value per salmon caught in the Deschutes is $87,400 ÷ 1,764 ≐ $50 per fish, although this is still too low because of our underestimate of salmon fishing trips. Of course, such an adjustment to fishing trips would not be possible without the creel-census data. Unfortunately, creel-census data were not available for most of the rivers in tables 1 and 2.

Creel-census data were available for the Alsea River. As was true for the Deschutes River, the 1977 salmon catch in the Alsea was greatly overestimated by the salmon and steelhead tag returns. Creel-census data indicated a catch of 283 adult chinook, 785 jack chinook, 96 adult coho, and 185 jack coho. This more accurate estimate of 1977 catch is far below the 2,290 salmon used in table 1. The overestimate of catch in table 1 was at least partially offset, however, by a similar overestimate of effort from our angler survey; this resulted in a corresponding overestimate of consumer

surplus for the Alsea in table 1. An overestimate of 6,651 for steelhead catch in the Alsea (table 2) is also indicated based on the creel-census data indicating a catch of only 4,599 for 1977. This overestimate of catch for the Alsea appears to be offset by a corresponding overestimate of fishing trips by our relatively small 1977 survey. Thus, the average value per steelhead in table 2 for the Alsea, $783,800 ÷ 6,651 ≐ $118, seems consistent with the creel-census data.

For the Deschutes River, we also overestimated steelhead fishing effort compared to the creel-census data. Our overestimate of effort and value for the Deschutes (table 2) appears to have been more than offset by the overestimate of steelhead catch for the Deschutes used in table 2. Thus, the average value per steelhead for the Deschutes computed from table 2, $847,500÷9,663 ≐ $88, seems slightly low based on the creel-census data.

Most of the difference in the average values per fish that can be calculated from tables 1 and 2 is due to sampling error, both in the estimated trips by river and in the catch estimates from salmon and steelhead tag returns. If creel-census data were available for most of the rivers in tables 1 and 2, then both the consumer surplus and the catch estimates could be corrected to give more accurate values per fish by river; unfortunately, creel-census data are available for only a few rivers. Some corrections might also be made by gathering data and information from fishery biologists near the various rivers, but limited time and resources precluded this.

Estimated Demand and Benefits Based on Adjusted Individual Observations Per Capita

Freshwater Salmon Angling

For the adjusted individual-observation approach, each individual observation was first multiplied by the same sample expansion factors used to estimate total salmon or steelhead angling trips. Then, each individual observation was divided by the share of the population in its distance zone. If, for example, five individual observations came from one zone with a population of 40,000, and if the first observation was expanded to represent 500 salmon angling trips, then 500 was divided by 8,000 (40,000 ÷ 5 = 8,000) to give a per-capita participation rate of 0.0625 (500 ÷ 8,000 = 0.0625). This procedure was similar to the traditional travel-cost model based on zonal averages but with only one observation per distance zone.

By following the above procedure for freshwater salmon angling for each of the nine rivers in table 3, we obtained 158 individual observations on participation rates per capita (along with 158 individual reports of travel costs and values for the other explanatory variables). Individual participation rates per capita were expressed as a function of various explanatory variables. The following semilog model was one of the better models fitted:

$$\ln(TRPSCAP)_{ij} = \underset{(-4.44)}{-2.693 - 0.02175\ RTC_{ij}} + \underset{(2.19)}{0.00004939\ S\text{-}SEQP_{ij}} \quad n = 158 \quad R^2 = 0.131 \ . \tag{19}$$

Table 3—Estimated consumer surplus by river for 1977 Oregon freshwater salmon sport anglers, based on participation rates per capita

River	Estimated catch of salmon[a]	Traditional estimate of consumer surplus per river[b]	Gum-Martin[c] estimate of consumer surplus per river[b]
		Dollars	
Alsea	2,290	498,000	459,800
Clackamas	2,149	1,493,400	553,300
Columbia	13,172	3,896,500	3,347,300
Coos	573	190,600	78,900
Deschutes	3,833	111,400	208,900
Rogue	8,864	641,600	557,200
Umpqua	4,570	710,700	1,511,500
Willamette	14,222	3,255,000	3,980,100
Wilson	4,692	123,000	383,000
Total	54,365	10,920,200	11,080,000

[a] Reported by Oregon Department of Fish and Wildlife.

[b] Estimated from equation (19).

[c] Gum and Martin 1975.

The variables in (19) are shown by the same symbols as in the travel-cost model in equation (3); RTC_{ij} is the travel cost of the *jth* observation in the *ith* distance zone and cost of travel time is assumed to be one-third of the wage rate. The variable $S\text{-}SEQP_{ij}$ is the replacement value of fishing equipment and related supplies used for salmon and steelhead fishing.

The important travel-cost coefficient in equation (19) is less than one-half in absolute magnitude of its counterpart in the traditional zonal-average travel-cost model (equation 3). This smaller travel-cost coefficient implies a value per trip of nearly $46, which is more than twice the estimate from the zonal-average travel-cost model for freshwater salmon angling (equation 3). One possible problem with equation (19) is the likelihood of a considerable amount of error in the travel costs reported by the respondents in our survey, especially when some trips were made 2 or 3 months before the questionnaire was sent.

A marginal Gum-Martin consumer surplus per fish of about $225 was computed as a result of fitting consumer surplus by river as a linearly homogeneous function of catch (as in tables 1 and 2).

Ocean Salmon Angling

Individual participation rates per capita for ocean salmon fishing were fitted as a function of various explanatory variables. The following regression was one of the more satisfactory models fitted:

$$\ln(TRPSCAP)_{ij} = -2.700 - 0.01191\ RTC_{ij} \quad n = 211 \quad r^2 = 0.282\ . \qquad (20)$$
$$(-9.05)$$

Variables in (20) are shown by the same symbols used in equation (19). The travel-cost coefficient in (20) is less than one-half of the absolute magnitude of the travel-cost coefficient for the zonal-average travel-cost model of equation (15) (same as for freshwater fishing). The smaller absolute value of the coefficient in (20) implies a value per trip of about $84, or over 50 percent more than the earlier estimate from the zonal-average travel-cost model of equation (15). Similarly, the value per fish is 50 percent more than the estimate from the zonal-average travel-cost model. Dividing the total Gum-Martin consumer surplus estimated from (20) by the total ocean salmon catch for 1977 yields $81 per fish ($21.24 million ÷ 260,683 ≐ $81).

One limitation of benefit estimates based on equation (20) is the measurement error bias in the travel-cost coefficient, as mentioned in the preceding section for freshwater salmon angling. A detailed discussion of the pros and cons of the various estimates is presented in chapter 5.

Summary and Conclusions

Various estimates of consumer surplus per trip and per fish from the zonal-average travel-cost model and from the model for individual observations per capita are presented in table 4. For freshwater fishing, the consumer-surplus estimates based on the individual observations per capita are more than twice as high as the estimates from the traditional zonal-average travel-cost model. For ocean fishing, the consumer surplus estimates from the individual observations per capita were about 40 percent higher.

We believe that the higher consumer-surplus estimates from the individual observations per capita resulted from the bias caused by travel-cost measurement error. A substantial error in reporting trip expenses was likely the result of respondents being asked to list expenditures made for fishing trips that were taken as much as 3 months before they received the questionnaires. Hiett and Worrall (1977) found that marine anglers made substantial recall errors when questioned about their fish catch and fishing effort, especially if questioned more than 60 days after their fishing trip.

If large reporting errors of trip costs occurred, as seems likely, then substantial bias in the estimate of the important travel-cost coefficient also occurred. Various authors (for example, Johnston 1972) have shown that the probability limit of the ordinary least squares estimate of the regression coefficient β is:

$$\text{plim}\ \beta = \frac{\beta}{1 + \sigma_v^2 / \sigma_x^2}\ , \qquad (21)$$

where σ_v^2 is the variance of the measurement error in reported travel costs, and σ_x^2 is the variance of the true travel-cost values. Equation (21) shows that a large measurement error causes an underestimate of the travel-cost coefficient, which causes a corresponding overestimate of consumer surplus. It also follows from (21) that the bias

Table 4—A comparison of consumer surplus values for salmon sport fishing, estimated by various methods

Salmon sport fishing	Gum-Martin consumer surplus method[a]		
	Total	Average per fish[b]	Average per trip[c]
	Million dollars	- - - - - *Dollars* - - - - -	
Freshwater:			
Zonal-average, equation (3)	$ 4.723	$ 87	$19
Individual per capita, equation (19)	11.080	225	46
Ocean:			
Zonal average, equation (15)	13.726	53	54
Individual per capita, equation (20)	21.240	81	84

[a]Gum and Martin 1975.

[b]Computed by dividing total Gum-Martin consumer surplus by the total number of fish caught.

[c]Computed by dividing total ocean consumer surplus (per Gum-Martin) by the total number of trips, 253,000 and the total freshwater consumer surplus by 243,000 trips.

from measurement error is substantially reduced by the zonal-averaging process used in the traditional travel-cost model; the reason is that the variance of a mean is equal to σ^2/n, and σ_v^2 in (21) is thereby reduced in the zonal-average travel-cost model while σ_x^2 remains essentially unchanged. Plim β therefore tends to β for travel-cost models with zonal-averages having large numbers of observations. Even for small numbers of observations per distance zone, however, the bias from measurement error is greatly reduced (Brown and others 1983).

The preceding discussion was not meant to imply that the consumer-surplus values from the traditional zonal-average model in table 4 were necessarily the "true" values and any others were false. The true values are, of course, unknown, and the best value of travel time is really not known. If the true value of travel time were actually two-thirds or more of the wage rate, rather than the one-third used in our travel-cost models, then our zonal-average travel-cost models would give too low an estimate of consumer surplus. Nevertheless, based on present knowledge, we believe that the estimates of consumer surplus from our zonal-average travel-cost models are the most reliable and accurate of any travel-cost models fitted for this study.

Acknowledgment

We thank Chris Carter, Oregon Department of Fish and Wildlife, for cooperation in providing 1977 creel-census data collected by Bob Lindsey, Nancy MacHugh, and Bob Mulen. We thank Elizabeth Strong, resource economist, Yuma, AZ, for letting us use the steelhead travel-cost data she developed.

Literature Cited

Bockstael, Nancy E.; McConnell, Kenneth E. 1981. Theory and estimation of the household production function for wildlife recreation. Journal of Environmental Economics and Management. 8: 199-214.

Brown, William G.; Sorhus, Colin; Chou-Yang, Bih-lian; Richards, Jack A. 1983. Using individual observations to estimate recreation demand functions: a caution. American Journal of Agricultural Economics. 65(1): 154-157.

Gum, Russell L.; Martin, William E. 1975. Problems and solutions in estimating the demand for and value of rural outdoor recreation. American Journal of Agricultural Economics. 57(4): 558-566.

Hiett, R.L.; Worrall, J.W. 1977. Marine recreational fishermen's ability to estimate catch and to recall catch and effort over time. McLean, VA: Human Sciences Research Inc. 22 p.

Johnston, J. 1972. Econometric methods. New York: McGraw-Hill. 300 p.

Samples, Karl C.; Bishop, Richard. 1985. Estimating the value of variations in anglers' success rates: an application of the multiple-site travel-cost method. Journal of Marine Resource Economics. 2(1): 55-74.

Sorhus, Colin N. 1980. Estimated expenditures by sport anglers and net economic values of salmon and steelhead for specified fisheries in the Pacific Northwest. Corvallis, OR: Oregon State University. 142 p. Ph.D. thesis.

Sorhus, Colin N.; Brown, William G.; Gibbs, Kenneth C. 1981. Estimated expenditures by salmon and steelhead sport anglers for specified fisheries in the Pacific Northwest. Spec. Rep. 631. Corvallis, OR: Oregon Agricultural Experiment Station. 86 p.

Ward, Frank A. 1981. A review of problems and solutions in the use of the travel-cost method for valuing recreation resources. In: Gum, R.L.; Author, L.M., eds. Outdoor recreation and the public interest. Spec. Rep. 610. Corvallis, OR: Oregon Agricultural Experiment Station. 137-175.

Chapter 4: Empirical Results From the Travel-Cost Model: Individual-Observation Approach

Kenneth C. Gibbs[1,2]

Outdoor recreational demand functions have traditionally been based on average participation rates and on average travel costs for various distance zones; but some researchers argue that this averaging can reduce the content of the data set (Brown and Nawas 1973, Gum and Martin 1975). Some reservations have also been expressed about the use of individual observations (Brown and others 1983). It is therefore of interest to compare demand and benefit estimates for salmon angling derived by the unadjusted individual-observation approach with the earlier estimates derived from both the traditional zonal-average and the adjusted individual-observations models from chapter 3. A detailed discussion of the pros and cons of different approaches is presented in chapter 5.

[1] Research assistance provided by Ching-Kai Hsaio.

[2] KENNETH C. GIBBS was associate professor, Oregon State University, School of Forestry, Department of Resource Recreation, Corvallis, OR 97331; he is currently self-employed, Route 1, Box 46A, Baker, OR 97814.

Estimated Demands and Benefits

Freshwater Salmon Angling Based on Unadjusted Individual Observations

With the unadjusted individual-observation approach, each observation is used in the regression without adjustment to a per-capita basis. The unadjusted procedure uses each of the 158 observations as data points and regresses them without adjustment to the dependent variable. From this method, the following semilog model was chosen as best representing the data:

$$\ln(TRPS)_j = \underset{(11.68)}{1.17} - \underset{(-3.23)}{0.011}\ RTC_j + \underset{(3.09)}{0.00010}\ S\text{-}SEQP_j \quad n = 158 \quad R^2 = 0.11\ . \quad (1)$$

In this chapter, R^2 and r^2 are the proportion of variation in the mean-corrected dependent variable explained by regression. Numbers in parenthesis are t-statistics for the coefficients.

The variables in (1) are defined in chapter 3, except that in (1) only one subscript occurs for each observation. $TRPS_j$ is the number of salmon fishing trips the *jth* person took during the 3-month period in which the person was contacted. RTC_j is the revised travel cost for individual$_j$ with travel time assumed to be worth one-third of the wage rate. $S\text{-}SEQP_j$ is the replacement value of fishing and related equipment used for salmon and steelhead angling by individual$_j$. All estimated coefficients are statistically significant, but the magnitudes differ from previous estimates. The consumer surplus from equation (1) is valued at $61 per trip in the traditional method of calculation; however, a higher value of $92 per trip was obtained by using the Gum-Martin method.

Consumer surplus per trip based on the traditional method of computation was converted to a total value per river by using a procedure similar to that used in chapter 3. The consumer surplus per river was then used as the dependent variable, and estimates by the Oregon Department of Fish and Wildlife of catch by river were used as the independent variable to obtain the following regression:

$$CS_j = \underset{(7.39)}{304.39}\ CTCH_j \quad n = 9 \quad r^2 = 0.80\ . \quad (2)$$

A marginal value per fish of $304 is implied from (2).

Ocean Salmon Angling

The 211 unadjusted observations were used to regress the number of trips taken as a function of explanatory variables. The following semilog model was judged the most indicative of the data:

$$\ln(TRPS)_j = \underset{(10.07)}{0.74} - \underset{(-4.40)}{0.0036}\ RTC_j + \underset{(5.18)}{0.000064}\ S\text{-}SEQP_j \quad n = 211 \quad R^2 = 0.19\ . \quad (3)$$

Again, all estimated coefficients are statistically significant. Average consumer surpluses of $199 per trip (traditional method) and $277 per trip (Gum-Martin method) were calculated. These estimates were higher than those found by using other travel-cost methods.

Consumer surplus per fish can be calculated for ocean salmon fishing by dividing the total consumer surplus by the estimated ocean salmon catch. Total consumer surplus is determined by multiplying the consumer surplus per trip by the total number of ocean fishing trips. Data on ocean catch were obtained from Oregon Department of Fish and Wildlife. Each fish has an estimated average net economic value of $211.

Table 1—A summary of consumer surplus values of salmon sport fishing, estimated by various travel-cost methods[a]

Method	Average consumer surplus[b]	
	Per trip	Per fish
	Dollars	
Freshwater:		
Zonal-average	19	87
Individual per capita	46	225
Unadjusted individual[c]	61*/92	275*/411
Ocean:		
Zonal-average	54	58
Individual per capita	84	81
Unadjusted individual[c]	199*/277	211*/269

[a] Zonal-average and individual per capita values are from table 4, chapter 3.

[b] Computed by estimating the total consumer surplus and dividing by the total number of trips or by the total number of fish caught.

[c] All consumer surpluses were estimated by the Gum-Martin (1975) procedure, except for those numbers with an asterisk, which were computed by the traditional method.

Table 1 is helpful for comparing the various estimates of economic value per trip and per fish when different forms of the travel-cost method were used. The three forms of the travel-cost method gave quite different results, and arguments can be made for each of the three approaches. A comparison and evaluation of the travel-cost based estimates are presented in chapter 5.

Literature Cited

Brown, William G.; Nawas, Farid. 1973. Impact of aggregation on the estimation of outdoor recreation demand functions. American Journal of Agricultural Economics. 55(2): 246-249.

Brown, William G.; Sorhus, Colin; Chou-Yang, Bih-lian; Richards, Jack A. 1983. Using individual observations to estimate recreation demand functions: a caution. American Journal of Agricultural Economics. 65(1): 154-157.

Gum, Russell L.; Martin, William E. 1975. Problems and solutions in estimating the demand for and value of rural outdoor recreation. American Journal of Agricultural Economics. 57(4): 558-566.

Chapter 5: Fitting the Travel-Cost Model by Using Zonal Averages, Individual Observations, and Adjusted Individual Observations

Part I: Potential Weaknesses of the Unadjusted Individual-Observation Travel-Cost Model

William G. Brown and Ching-Kai Hsiao[1]

One advantage of estimating consumer surplus based on individual observations is that the data are not averaged, which reduces the informational content of the basic data set; that can be important if explanatory variables other than travel cost are included in the recreational-demand function (Brown and Nawas 1973, Gum and Martin 1975). Unfortunately, a corresponding disadvantage of using individual observations occurs if appreciable errors are made by some respondents in reporting their travel costs; these errors will cause bias in the estimated travel-cost coefficient—the well-known "measurement error" problem (Johnston 1972, p. 281-291). We believe some major errors occurred in the travel costs reported by some respondents to our survey, especially for those trips made 2-3 months before the questionnaire was distributed. Reported expenditures for food and lodging differed greatly among the respondents. Some economists have questioned including expenses for food and lodging in the travel-cost variable because the decisions on these costs are regarded

[1] WILLIAM G. BROWN is professor, Oregon State University, Department of Agricultural and Resource Economics, Corvallis, OR 97331. CHING-KAI HSIAO was research assistant, Oregon State University, Department of Agricultural and Resource Economics, Corvallis, OR 97331; he is currently employed by National Chung-Hsing University, Department of Agricultural Economics, Taichung, Republic of China.

as discretionary. Transportation costs to a given location generally show little difference because they are determined primarily by distance. Measurement error can be significant in individual travel costs and can lead to underestimating the absolute magnitude of the travel-cost coefficient and subsequent overestimating of consumer surplus (Brown and others 1983).

Averaging several observations can reduce the bias that comes from measurement error. The zonal-average method of estimating the travel-cost coefficient reduces the bias in the individual observation method (Brown and others 1983).

The bias from measurement error may explain why consumer surplus estimates based on individual observations are more than twice as large as estimates from the traditional zonal-average travel-cost model. The unadjusted individual-observation (UIO) approach results in an even larger estimated consumer surplus. We believe that the larger estimated consumer surplus from UIO is caused by two factors: (1) measurement error in travel cost, for the same reasons as already noted for the individual-per-capita approach; and (2) an additional bias in estimating the UIO travel-cost coefficient that occurs because of the way the dependent variable is specified. This second source of bias needs some explanation.

The desire by many researchers to estimate demand from the unadjusted individual observations is understandable. After all, the individual is the one who gains or loses from policies raising or lowering the price of a commodity. Thus, it seems intuitively appealing to estimate demand directly from the unadjusted individual observations rather than from aggregate per-capita figures that might not adequately reflect individual gains or losses from price changes.

Paradoxically, just the opposite occurs for various cases, with much more accurate estimates of the sum of individual consumer surpluses being obtained from the per-capita demand model than from the UIO approach. For example, a serious underestimation of the UIO travel-cost coefficient can easily occur under the following conditions: If the individual demand functions for persons in all distance zones are distributed symmetrically about some population-mean demand function, then only those persons with demand functions distributed above the population-mean demand function will participate from those zones farther away from the recreational site. Because the few people who do participate will still be taking some trips, however, the estimation of demand with UIO trips as the dependent variable will obscure the declining percentage of participants and result in underestimating the travel-cost coefficient as compared to an adjusted per-capita approach. The following simple case illustrates this possibility. Suppose that the "true" individual demand function for a given recreational activity is:

$$q_i = 6 - 1.0\ TC_i + \alpha_i\ , \qquad (1)$$

where α_i is a random "intensity" variable representing the difference in intensity of demand among recreationists. If $E(\alpha_i) = 0$, then the mean individual demand function is $E(q_i) = 6 - 1.0\ TC_i$. Note that α_i is not an error term but, rather, a variable denoting

the difference in intensity or strength of demand among various households. Assume, for illustration, that α_i is a discrete variable taking certain values distributed symmetrically about zero with the following probabilities:

$$E(\alpha_i) = \frac{1}{16}[-4 + 4(-2) + 6(0) + 4(2) + 4] = 0 , \quad (2)$$

then the variance of α_i would be:

$$E(\alpha_i - 0)^2 = \frac{1}{16}[(-4)^2 + 4(-2)^2 + 6(0) + 4(2)^2 + (4)^2] = 4 . \quad (3)$$

The distribution of α_i implied by (2) is the same as the distribution of the sum that can be obtained from flipping four unbiased coins where a tail is assigned a value of -1.0 and a head a value of +1.0. Thus, the probability is 1 in 16 of obtaining four tails that add up to -4 or four heads and a sum of +4. The probability of obtaining three tails and one head (equal to -2) is 4 in 16, with the same probability for three heads and one tail and a sum of +2. Finally, the probability of obtaining exactly two heads and two tails and a zero sum is 6 in 16. All the above probabilities follow from the binomial expansion, which is shown in some probability or statistics textbooks.

Consider equation (1) for the assumed individual demand function, and then consider the hypothetical travel-cost and distance-zone data shown in table 1, generated from equations (1) and (2). For distance zone 1, the expected number of trips per recreationist is 6 - 1 = 5, but some recreationists take more and some take less, depending on their "intensity of demand"; that is, depending on their α_i value. For example, the first line of numbers in table 1 corresponds to $\alpha_i = -4$; therefore, the number of visits per participant is 6 - 1 - 4 = 1. Because there is only one respondent, on the average, for this $\alpha_i = -4$, multiplying 1 times 1 times the sample blowup factor of 100 gives the estimated total number of visits of 100 for the first line. For the second line of numbers in table 1, corresponding to $\alpha_i = -2$, the estimated total number of visits in the next-to-last column is 3 times 4 times the expansion factor of 100, or 1,200. The other numbers for the main distance zone 1 are generated in the same way.

No potential participants are eliminated in zone 1 because the lowest intensity of demand and travel cost do not drive the q_i value to be equal to or less than zero. But for main distance zone 2, where the travel cost increases to 4, the respondent in the first line of zone 2 of table 1 with $\alpha_i = -4$ has predicted trips of $q_i = 6 - 4 - 4 = -2$. Because trips must be greater than or equal to zero, zero trips are indicated by such a respondent. For the second line of zone 2 with $\alpha_i = -2$, exactly zero trips are reported because $q_i = 6 - 4 - 2 = 0$. Thus, the total number of trips for these four respondents is zero. For distance zone 3 of table 1, with travel costs of $7 per visit, only the five respondents represented by the last two lines of numbers have sufficiently high intensities of demand, with $\alpha_i = 2$ and $\alpha_i = 4$, to take one or more trips. Thus, the sample number of participants drops from 16 to 11 to 5 in going from the nearest zone to the more distant zones, where all zones are assumed to have equal populations of 1,600.

Table 1—Observations generated for 3 distance zones where the true individual demand functions are assumed to be $q_i = 6 - 1.0\ TC_i + \alpha_i$, where $E(\alpha_i) = \frac{1}{16}[1(-4) + 4(-2) + 6(0) + 4(2) + 1(4)]$

Main distance zone	Population of main zone	Intensity of demand	Average travel cost per visit	Predicted total visits per participant	Number of respondents	Estimated total visits[a]	Zonal average visits per capita
			Dollars				
		-4	1	1	1	100	
		-2	1	3	4	1,200	
1	1,600	0	1	5	6	3,000	5.0
		2	1	7	4	2,800	
		4	1	9	1	900	
		-4	4	0	1	0	
		-2	4	0	4	0	
2	1,600	0	4	2	6	1,200	2.125
		2	4	4	4	1,600	
		4	4	6	1	600	
		-4	7	0	1	0	
		-2	7	0	4	0	
3	1,600	0	7	0	6	0	0.4375
		2	7	1	4	400	
		4	7	3	1	300	

[a] Assumes a random sampling of 1 percent of the general population and a corresponding expansion factor of 100.

How would the results in table 1 change if the α_i values were distributed differently; for example, if the α_i were distributed normally with mean zero and variance equal to four? Actually, a similar result can be obtained for most symmetric distributions with similar means and variances.

Fitting the UIO demand function by ordinary least-squares in table 1 gives exactly the same regression coefficients as does defining the dependent variable as equal to the average number of trips per participating recreationist in each zone. This observation can be used as many times as the number of recreationists observed for that zone; that is, the average number of trips per recreationist can be used 16 times as the dependent variable in zone 1, 11 times in zone 2, and 5 times in zone 3 to obtain exactly the same regression coefficients as were obtained by fitting the UIO model. The UIO approach clearly gives an estimated travel-cost coefficient that is ideal for estimating the average number of trips per participating recreationist for a given zone,

but not good at all for predicting the total number of trips to be taken in a zone with a given travel cost! The ordinary least squares equation obtained from the UIO approach is:

$$q_i = 5.5862 - 0.6080\ TC_i\ . \qquad (4)$$

An average consumer surplus per participating recreationist of about $20.38 is obtained by computing the traditional consumer surplus from (4) for zone 1. Multiplying $20.38 by the assumed 1,600 participating recreationists in zone 1 yields an estimated total consumer surplus for zone 1 of about $32,608. For zone 2, the same procedure gives 1,100($8.182) ≐ $9,000, and for zone 3, 500($1.455) ≐ $728. Thus, a total consumer surplus of about $42,336 from the UIO approach is obtained.

How accurate is the preceding UIO estimate? It is easily checked by computing the individual consumer surpluses from the assumed true demand function, $q_i = 6 - 1.0\ TC_i + \alpha_i$. For the first line of numbers in table 1, the true individual demand function is $q_i = 2 - tc_i$, and it represents one sample observation. This consumer surplus is equal to (0.5)(1)(1) = 0.5. A true consumer surplus of $50 is obtained by using an expansion factor of 100. Similarly, for the second line of numbers in table 1, the true demand function is $q_i = 4 - tc_i$, which implies three trips by this type of participant. A true consumer surplus equal to (0.5)(3)(3), or $4.5 per participant, is computed. Because four observed recreationists of this type are included in line 2 of table 1, the total consumer surplus represented by line 2 is 400($4.5) or $1,800. By following this same procedure for the rest of table 1, a total true consumer surplus of $30,050 is obtained. In this example, the UIO approach overestimated the true consumer surplus by $12,286, or about 41 percent.

Of course, the amount of overestimation bias that may result from the UIO approach could vary greatly from the 40 percent in the assumed conditions of table 1. If distances and travel costs are such that the participation for the more distant zones declines more rapidly than is shown in table 1, then an even greater overestimation of consumer surplus could result from the UIO approach. On the other hand, smaller rates of decline would result in a smaller upward bias from using the UIO method.

Comparing the error in estimating consumer surplus from the UIO method with that from the traditional zonal-average travel-cost model is of interest. If the last column in table 1 (the zonal-average visits per capita) is used as the dependent variable, the zonal-average travel-cost estimate of the demand function is:

$$y_i = 5.5625 - 0.760417\ TC_i\ . \qquad (5)$$

In (5), the traditional estimate of consumer surplus is 1.51627 × 1,600 ≐ $24,260. For zone 2, estimated consumer surplus is $4.1784 × 1,600 ≐ $6,685 and only about $60 for zone 3. Thus, a total consumer surplus of about $31,005 is estimated by the zonal-average travel-cost model—an amount fairly close to the true consumer surplus of $30,050. The error of estimation was only about 3 percent, which is much better than the 41-percent error in the UIO method.

The specific numerical results from table 1 should not be generalized. The numerical results are presented only to illustrate the consequences that follow from the basic, logical defects of the simple UIO approach. Sampling errors in the data will cause the specific numerical results to change from one sample to another. Nevertheless, the results from table 1 indicate that estimates of consumer surplus from the UIO approach will not be very accurate, on the average, when a significant decline in the participation rate by the population in the more distant zones occurs.

We wondered if conditions existed under which the UIO approach would give accurate estimates of the true demand-function coefficients and of consumer surplus. The only condition we have found that assures accuracy from the UIO approach is where no variation exists in demand among the participants. (In this case, no decline in participation rates with increasing distance would occur until distance became great enough to cause zero participation.) This condition seems rather unrealistic because great variation occurs in the number of trips taken by individuals incurring similar travel costs.

Some empirical evidence exists that the estimates of value from the zonal-average travel-cost model are likely more accurate than the value estimates based on the two individual-observation approaches. In a carefully planned and well-executed study, Crutchfield and Schelle (1978) used a contingent-value approach to estimate consumer surplus. The approach was based on the willingness of Washington salmon anglers to pay and to sell. Crutchfield and Schelle estimate an average consumer surplus based on willingness to sell of $40 per ocean-salmon fishing-day (1978 prices) with a $500 upper limit, $55 per day with a $1,000 upper limit, and $75 per day with a $2,000 upper limit.

In contingent-value studies, estimates of value based on willingness to sell are on the high side as compared to values based on direct questions about willingness to pay, which usually tend to be much lower. Bishop and Heberlein (1979), in their study of 1978 permits for goose hunting for the Horicon Zone of east-central Wisconsin, found an average consumer surplus of $101 per permit based on hypothetical willingness to sell. The average surplus based on willingness to pay was on $21 per permit. Actual cash offers revealed a "true" average consumer surplus of $63.

In a comparison with the Crutchfield and Schelle estimates, Sorhus (1980) used a zonal-average travel-cost model, with no assumed cost of travel time, to estimate an average consumer surplus of $45 per day for Washington ocean sport salmon anglers. The individual per-capita estimates of consumer surplus for both freshwater and ocean angling are 2.42 and 2.24 times as high, respectively, as the corresponding zonal-average estimates of consumer surplus per trip in table 4, chapter 3. Applying this factor to Washington ocean salmon sport fishery gives $2.24 \times \$45$ or about $100 per day—much too high given the Crutchfield-Schelle results.

Because true values are unknown, we cannot state with certainty that any one estimate in table 4, chapter 3, is precisely correct and that other estimates are correspondingly incorrect. Nevertheless, our conclusion, based on econometric considerations and the available empirical evidence, is that the zonal-average estimates seem much more likely to reflect what the anglers would, on average, actually be willing to pay. More research is needed to fully evaluate the estimating methods under various specified conditions.

Part II: Potential Weaknesses of the Zonal-Average and Adjusted Individual-Observation Travel-Cost Models

Kenneth C. Gibbs[2]

The three methods used in this report to estimate the travel-cost demand for salmon fishing yield quite different estimates of consumer surplus. The question is, which is best? Unfortunately, the true value is not known, so a comparison among the three becomes difficult. No arguments about the differences among the estimates are convincing; the underlying properties of the methods themselves must be evaluated. The choice among models must be based on their logical and internal consistency, which sounds simpler than it is. A detailed comparison might be a study in itself. I will concentrate on potential weaknesses of the zonal-average travel-cost model.

While I recognize weaknesses in all methods that estimate something as difficult as economic value of a recreational activity, I believe some cautions should be observed when the zonal-average travel-cost method is used.

Arguments to convince us that the zonal average exhibits less bias than do individual observations concentrate on the relative magnitude of the estimates (Brown and others 1983). The "true" value is calculated, with known data, by using a zonal approach wherein consumer surplus is estimated for each zone and the estimates are summed. An estimate using individual observations is compared to this, and the difference is used as evidence of a bias. A difference is bound to exist. All such arguments become "example specific" in that other examples can be constructed to show the opposite result. This, it seems, is not the direction to spend energy.

One of the obvious outcomes of averaging data is the loss of information. What do these few average observations, used in the statistical estimation, really mean? After all, it is the individual who is making the decision on recreation, not an average over several individuals. Surely, no one knows what a zonal-average decisionmaker is. The aggregation problem in recreational studies must be directly confronted.

Related to the loss of information from the data is a concern for the validity of the statistical properties. It seems misleading to put any degree of faith in a t-value or R^2 when the data have been averaged. The zonal-average model gives an improved statistical fit because much of the variation in the data has been eliminated. For example, the R^2 statistics presented in chapter 3 for both the zonal-average and the adjusted individual methods for freshwater and ocean salmon fishing are as follows:

Method	Freshwater salmon	Ocean salmon
Zonal-average	0.815	0.661
Adjusted-individual	7.130	.207

[2] KENNETH C. GIBBS was associate professor, Oregon State University, School of Forestry, Department of Resource Recreation, Corvallis, OR 97331; he is currently self-employed, Route 1, Box 46A, Baker, OR 97814.

A significant improvement in the R^2 is observed when the data have been averaged, but this should not be interpreted that more faith can be placed in the results from the zonal-average model. Simply, economists are better at explaining the reactions of a mythical "zonal-average fisherman"—which does not exist. The real problem arises when economic results are interpreted and used by noneconomists for policy decisions. The high degree of statistical precision is misleading. Many professional economists likewise delude themselves into believing the zonal-average model is more trustworthy because of its statistical properties.

A question must be raised about interpreting data gathered from anglers that is adjusted by dividing by the zonal population. Many of the people in the zone never fish, so why include them in the group that does? The only respondents were those who took fishing trips.

A more serious shortcoming with the zonal-average model is the arbitrary nature of defining the zones. How many zones should be defined? How many observations should occur in each zone? The consumer-surplus estimates differ depending on how the zones are defined, but how do we know correct zonal definitions will be made? For this report, two definitions were used: the first with 37 zones for freshwater and 21 zones for ocean salmon, and the second with 158 and 211 zones, respectively (this is the adjusted individual-observation method). As indicated in table 4, chapter 3, the estimates from the adjusted individual model are about 2.1 to 2.5 times as large as the zonal average. The adjusted individual model, an extreme case of the zonal-average method, illustrates the magnitude of the problem—we are never really certain the zones have been defined to give the "best" estimate of consumer surplus. Why is it being argued that 37 and 21 zones are preferred to 158 and 211? What logic, theory, or intuition is being used to convince us? Why not only two zones? This problem appears to be one of the most serious drawbacks of the zonal-average method.

A great deal of concern has surfaced over the variation in the travel costs among respondents (Brown and others 1983). They conclude that this variation is at least partly the result of measurement error, and that averaging the data will help eliminate this econometric problem. I believe that averaging data may alleviate the problem only if the objective were merely econometrics, but an even more serious underlying problem is covered up by averaging. The real issue is one of defining the commodity consumed more precisely. Not just one commodity, called a "salmon fishing trip," exists. Motivation for the trip (to get out of the house, to put meat on the table, to socialize with friends), as well as an intangible element referred to as "quality," must be considered. Ignoring or refusing to deal with these issues is the reason for most of the difference in a variable such as travel costs. Economists need to work with other social scientists to better define the activity in which participation is observed. We do further injustice to scientific endeavors by covering up problems with a technique such as averaging data. Much more work is needed in this area—let us not stop with the zonal-average model and think we have solved the problem. We are indebted to people like Brown and others (1983) for pointing out the issue with the travel-cost variable, but we now need to work on solving the problem.

We still cannot conclude to everyone's satisfaction that one model is clearly superior to others. This discussion has attempted to point out some of the weaknesses only in the zonal-average approach. To choose a particular method, we have to weigh the pros and cons of each and decide accordingly. More research is needed to empirically and theoretically study these issues. The study reported herein certainly was a step in the right direction.

Literature Cited

Bishop, Richard C.; Heberlein, Thomas A. 1979. Measuring values of extra market goods: are indirect measures biased? American Journal of Agricultural Economics. 61(5): 926-930.

Brown, William G.; Nawas, Farid. 1973. Impact of aggregation on the estimation of outdoor recreation demand functions. American Journal of Agricultural Economics. 55(2): 246-249.

Brown, William G.; Sorhus, Colin; Chou-Yang, Bih-lian; Richards, Jack A. 1983. Using individual observations to estimate recreation demand functions: a caution. American Journal of Agricultural Economics. 65(1): 154-157.

Crutchfield, James A., Jr.; Schelle, Kurt. 1978. An economic analysis of Washington ocean recreational salmon fishing with particular emphasis on the role played by the charter vessel industry. Seattle: University of Washington, Department of Economics. 55 p.

Gum, Russell L.; Martin, William E. 1975. Problems and solutions in estimating the demand for and value of rural outdoor recreation. American Journal of Agricultural Economics. 57(4): 558-566.

Johnston, J. 1972. Econometric methods. 2d ed. New York: McGraw-Hill. 300 p.

Sorhus, Colin N. 1980. Estimated expenditures by sport anglers and net economic values of salmon and steelhead for specified fisheries in the Pacific Northwest. Corvallis, OR: Oregon State University. 142 p. Ph.D. thesis.

Chapter 6: Valuing Oregon Steelhead by Using a Household-Production Approach

Elizabeth J. Strong and Darrell L. Hueth[1]

In this chapter, we will present an empirical household-production (HP) model for steelhead sport fishing at selected rivers in Oregon. Two different specifications of the model are given, and two different regression techniques were used to obtain estimates of the parameters of each model specification. The first model is used to derive exact welfare measures of the mean value of a fishing experience and the mean value of a sport-caught fish. The second empirical model includes policy-related quality variables and is used to demonstrate techniques for evaluating the welfare effects of exogenous quality changes on anglers.

First, we describe HP theory and discuss econometric considerations. Then, we develop the specification of the basic HP model for steelhead fishing and describe the data used in this study. Further into the chapter, the parameter estimates obtained for the first model and the value estimates derived from this model are presented. The parameter estimates obtained for the second HP model are also presented, and techniques for determining the benefits of exogenous quality changes are outlined. At the end, we summarize the techniques used and the results.

[1] ELIZABETH J. STRONG was research assistant, Oregon State University, Department of Agricultural and Resource Economics, Corvallis, OR 97331; She is currently a resource economist, Yuma AZ. DARRELL L. HUETH was professor, Oregon State University, Department of Agricultural and Resource Economics, Corvallis, OR 97331; he is currently professor, University of Maryland, Department of Resource Economics, College Park, MD 20472.

Household-Production Method

The HP method, as developed by Becker (1965), is based on the notion that households (or individuals) combine purchased bundles of goods and time allocations to produce nonmarket goods (called commodities). Utility is not considered to be derived directly from market goods—as is assumed in the standard neoclassical framework—but rather indirectly through the production (and concurrent consumption) of commodities.[2] The decisionmaking framework for the household is based on two theories: the theory of the firm and the theory of consumer behavior. As pointed out by Michael and Becker (1973), one advantage of using both theories is that differences in behavior across households can be attributed to differences in technology (or production efficiency) in addition to differences in tastes. This is where the HP method departs from the traditional neoclassical framework, which attributes any differences in consumer behavior not accounted for by the usual demand determinants solely to differences in tastes.

In the HP framework, the household maximizes utility for commodities, subject to the conditions that the cost-minimizing combinations of inputs are used and that the budget constraint is satisfied. The model contains two sets of endogenous variables: (1) market and time inputs and (2) commodities. Exogenous variables include market prices for goods, environmental conditions (or the state of technology), and the amount of full income available for household production activities. Full income is defined by Becker (1965) as the amount of money income available (both earned and unearned) plus the opportunity cost of nonwork time.

The time and money available for producing commodities are interdependent because the time spent working for pay determines both earned income and time left over for household-production activities. When an HP model is constructed, either labor time is assumed to be fixed (and hence, both earned income and available time for household production are fixed) or full income is assumed to be fixed. Fixing full income in the model assumes that the household has the flexibility to alter its allocations between work and household-production activities.

The production technology is described by the parameters of the household's cost function (that is, the technology parameters). Assuming no jointness in production, the total cost function for m commodities is defined as:

$$C(z,p,w,A,\alpha) = \min_{x,t} \{ \sum_{i=1}^{m} [p_i x_i + w_i t_i \mid z_i = F_i(x_i, t_i, A_i, \alpha_i)]\} ,$$

where z is the 1-by-m vector of commodities; p_i is the vector of prices for x_i which is the 1-by-n_i vector of market goods used in the production of z_i; w_i is the opportunity cost of t_i, which is a scaler representing household time used to produce z_i; A_i is the

[2] For this discussion, utility was assumed not to be derived directly from time spent in household-production activities.

vector of technology variables for the *ith* production process; α_i is the vector of unknown technology parameters that describe the *ith* production technology; and F_i is the production function for the *ith* commodity. In the cost function itself, $p = (p_1,. . ., p_m)$ is a composite vector of

$$N = \sum_{i=1}^{m} n_i$$

prices, $w = (w_1,. . ., w_m)$ is the vector of m opportunity costs,
$A = (A_1,. . ., A_m)$ is the composite vector of technology variables, and
$\alpha = (\alpha_1,. . ., \alpha_m)$ is the composite vector of technology parameters.

Cost-minimizing demand equations for x and t can be derived from the cost function by way of Shepherd's lemma, which states:

$$\partial C/\partial p_i = x_i^* = f_i(p_i,w_i,A_i,z_i,\alpha_i) \text{ , and}$$

$$\partial C/\partial w_i = t_i^* = r_i(p_i,w_i,A_i,z_i,\alpha_i) \quad i = 1,. . ., m ;$$

where each f_i is a system of n_i demand functions. Both f_i and r_i represent partial-equilibrium demand functions because they are based on a given set of commodity-choice values.

Commodity-choice values are based on the usual determinants of consumer demand; that is, the quantity demanded of each z_i depends on its own price, the prices of related commodities, and the amount of available income. Because commodities are usually nonmarket goods, they generally do not have market-determined prices. As an alternative to using market prices, the HP method treats marginal costs as shadow prices for the commodities.

Each of the m marginal cost functions is defined as:

$$\partial C/\partial z_i = \pi_i = \pi_i(p_i,w_i,A_i,z_i,\alpha_i) \quad i = 1,. . ., m .$$

In general, each marginal cost depends on the quantity produced of the respective commodity, which leads to nonconstant shadow prices. A constant π_i arises if and only if the cost function is linearly homogeneous in z_i. If the π_i's are constant, they can be treated as fixed prices in the commodity-demand functions, which would then resemble standard neoclassical demand functions. Unlike standard neoclassical demand functions, however, these commodity-demand functions depend on shadow prices conditioned on technology factors, which generally vary across households.

Commodity-demand functions can be specified by using Roy's identity, which in the simple case of nonjoint constant-returns-to-scale (CRS) technologies, states that:

$$-\frac{\partial V/\partial \pi_i}{\partial V/\partial \mu} = z_i^* = G_i = G_i(\pi,\mu,\gamma) \quad i = 1,\ldots, m ;$$

where V is the indirect utility function; π is the 1-by-m vector of shadow prices; μ is the predetermined (exogenous) level of full income,[3] and γ is the set of unknown taste parameters. The household's indirect utility function is defined as:

$$V(\pi,\mu,\gamma) = \max_z \{U(z,\gamma) \mid \mu = \pi' z\} ;$$

where U is the direct utility function.[4]

The complete HP model as defined above is comprised of 2m plus N equations, including m commodity-demand equations, m time-input demand equations, and N market-good demand equations. The input demand equations can be specified in either their partial equilibrium forms (as shown above) or their general equilibrium forms. The former specification includes only the technology parameters; the latter includes both the taste and technology parameters.

---

[3] If time allocations between work and household-production activities were assumed to not be fixed, then full income would be equal to $\mu = \overline{w}T + Y$; where T is the fixed amount of total time available for both work and household-production activities, $\overline{w}$ is the wage rate, and Y is the fixed amount of unearned income. If the opportunity cost of household-production time were assumed to not be equal to the wage rate, however, then μ could not be treated as an exogenous variable because it would be dependent on the allocations of time between work and household-production activities.

[4] Pollak and Wachter (1975) and others claim that G is not a valid system of demand functions where the shadow prices depend on commodity-choice values (that is, under conditions of joint production or nonconstant returns to scale, or both); however, Barnett (1977) demonstrates that they are valid structural-demand functions under conditions of joint production and CRS. We showed that they are also valid in the absence of CRS as long as the cost function is homogeneous in z. Under this homogeneity condition, we defined the structural commodity demands as:

$$-\frac{\partial V/\partial \pi}{\partial V/\partial I} = z^* = G(\pi,I,\gamma) ;$$

where implicit income $I \equiv \pi' z$. The homogeneity condition guarantees that implicit income is an exogenous variable because $I = k \cdot \mu$, where k is the returns-to-scale parameter.

General-equilibrium demand equations are the reduced forms of the cost-minimizing demands; they account for optimal adjustments in the commodity markets.[5] This system of general-equilibrium-input demand equations can be used to estimate the taste and technology parameters. This approach is especially useful when data on commodity quantities are not available or commodities are not observable. Barnett (1977) points out some problems associated with this approach, such as the usual confounding of taste and technology parameters in the general equilibrium demand system and the possibility of biased parameter estimates resulting from estimating an incomplete system of equations.

Several other approaches can be used to obtain estimates of the taste and technology parameters. Barnett (1977) and Pollak and Wachter (1977) outline various techniques and discuss their advantages and disadvantages. Barnett recommends simultaneous estimation of the complete system of demand equations in their structural forms; that is, the demand functions denoted by G, f, and r.

Pollak and Wachter (1977) argue that restricting the HP model to situations where "...estimation of the structural parameters of complete systems is possible severely reduces its usefulness as a framework for empirical work." They propose estimating either the complete system of structural input demand equations and reduced-form commodity-demand equations or the complete system of reduced-form input and reduced-form commodity-demand equations. Both of these approaches are likely to involve confounding taste and technology parameters, however; and separating the two may not always be possible. And even if the parameters can be separated, deriving structural parameter estimates from the given estimates of reduced-form parameters may not always be possible. Where structural parameter estimates are desired, the preferred procedure is to simultaneously estimate the complete system of structural demand equations; Barnett's results indicate this approach is valid even with nonconstant shadow prices.

Another way to obtain structural parameter estimates through simultaneous-equations estimation is to use a two-stage procedure. In the first stage, the technology parameters are estimated; and in the second stage, taste-parameter estimates, which are conditioned on the predetermined technology-parameter estimates, are obtained. This approach may be useful when data or money are not sufficient for estimating a complete system of structural demand equations. Of course, with this approach, the possibility exists of a simultaneous-equations bias in the parameter estimates.

---

[5] The general equilibrium-input demand functions can be derived in two ways. The first is to substitute each of the reduced-form commodity demand functions, $g_i(p,w,A,\mu,\gamma,\alpha,k) \equiv G_i(\pi(p,w,A,z,\gamma),\mu \cdot k)$, for each z_i in the cost-minimizing demands f and r. The reduced-form system (g) can be derived without knowledge of the underlying structural system (G) by solving the problem of maximizing utility, $U = U(z,\gamma)$, subject to the generally nonlinear constraint $\mu = C(z,p,w,A,\alpha)$, which may or may not be homogeneous in z. The second way is to apply Roy's identity to what is called the "implied" indirect utility function, which is defined as:

$$L(p,w,A,\mu,\gamma,\alpha) = \max_{x,t} W(F(x,t,A,\alpha),\gamma) \mid \mu = p'x + wt ;$$

where W is the "implied" direct utility function in input space, which is obtained by substituting the production functions (F) for z in the utility function $U = U(z,\gamma)$.

We present two sets of results for the structural taste and technology parameters of an HP model for steelhead fishing. The two sets pertain to two different specifications of the model. The first set of results were obtained by estimating the complete system of structural demand equations for steelhead fishing. The second set was obtained in two stages by using a single-equation estimation procedure.

The Conceptual Model for Steelhead Fishing

Data on steelhead fishing activities were obtained through a survey of about 1.5 percent of the anglers who purchased Oregon fishing licenses in 1977. Of the 9,000 questionnaires mailed throughout the year, about 55.6 percent were returned. We used the 417 of these questionnaires that contained information on fishing trips taken primarily to fish for steelhead (see appendix to chapter 1).

The model used in this study was based on Bockstael and McConnell's (1981) framework, which views the fishing trip and the fish caught per trip as two utility-yielding characteristics of a fishing experience. Unlike other valuation techniques for recreation, this method assumes that anglers can influence their catch rates at any site by varying the quantities and types of fishing used. Of course, exogenous factors also determine catch rates; these include the quality of the site, the angler's experience, and the type of fishing equipment. These factors influence an angler's efficiency in producing a certain fish catch per unit of time. Anglers also use various forms of transportation to produce fishing trips to a given site. The angler's efficiency in producing fishing trips depends on the distance traveled to the site and the type of transportation.

We know from the data in the questionnaires that anglers took trips primarily to fish, so viewing these trips as single-purpose trips seems reasonable. Relevant commodities for a given angler therefore are:

z_1 = the number of fishing trips taken to a given river during a given quarter of the year, and

z_2 = the number of steelhead caught at a given river during a given quarter.

One-quarter of a year was used for two reasons: (1) the questionnaires were sent on a quarterly basis with information requested for the previous 3 months; and (2) assuming that fishing success rates differ from one quarter to another seems reasonable, mainly because of fish-run patterns but also because of differences in weather that can influence water quality and fish catchability. Variables can be put in the production function for quarterly fish catch to account for differences in quality across the four quarters of the year. If the model is estimated with data from several sites, then variables can be placed in the production function for fish catch to account for differences in quality across the sites.

We assumed that the 29 rivers in this study were similar enough to permit specifying an HP model describing production and consumer-demand relationships for a representative river. Although developing a multiple-site model would be preferable to allow for differences in fishing and traveling efficiencies and in angler behavior from one river to another, this type of analysis was not possible here because of deficiencies in the data. An advantage of pooling data across numerous rivers was that variability in site quality across the sample could be achieved.

The data were not originally obtained to develop a multiple-site model; nor were they obtained to apply the HP method. Nevertheless, the questionnaires do provide most of the information needed to empirically specify an HP model. The respondents were asked, for example, to record their expenditures for certain types of fishing inputs (guide service, bait, and lures) and traveling inputs (gas, food, and lodging), the distance traveled, the time spent fishing, the number of fish caught per trip, and the number of trips taken. Also, fairly detailed information on expenditures for fishing equipment was requested.

The major limitation of the data was that information on variable inputs, fish catch, and fishing sites was not obtained for every trip during the quarter, but only for the last three trips taken by the angler during the quarter. This means that the quarterly variables (especially quarterly fish catch and input quantities) were constructed from information pertaining only to the angler's last three trips. These quarterly variables were calculated for each angler by multiplying the number of fishing trips taken to each river during the given quarter (z_1) by the mean fish catch (and mean input levels) per trip. Each angler could have a maximum of three observations for the variable z_1 because each angler was able to report visiting up to three different rivers during the quarter. For each angler, the z_1 variable was determined for each river based on the distribution of the last three trips among all rivers mentioned. All these procedures required the assumption that the last three trips taken during a given quarter were representative of all trips taken during that quarter.

Besides the lack of independent observations on quantities of commodities and inputs, another problem with the survey data was that separate data on prices and quantities of market goods were not requested. Because no price-index data existed for converting expenditure figures into quantity indices, the quarterly expenditures on classes of market goods were used as proxies for quantities of market goods in the production functions. This procedure required the assumption that prices of market goods are constant across the sample area. We know that using expenditures as proxies for quantities in the production functions, and the necessary exclusion of market goods prices from the model, can lead to biased estimates of technology parameters.

The variable inputs for producing z_1 are defined for a representative angler as:

x_1 = expenditures for gas, vehicle maintenance, food, and lodging on steelhead fishing trips to a given river during a given quarter; and

t_1 = the number of hours spent traveling on steelhead fishing trips to a given river during a given quarter.

The variable inputs for producing z_2 are defined as:

x_2 = expenditures for guide service, bait, and lures used to fish for steelhead on a given river during a given quarter; and

t_2 = the number of hours spent fishing for steelhead at a given river during a given quarter.

Because the price variables have to be included to use the dual approach (which starts with a specification for the cost function), the primal approach was used to derive the cost function—and hence for the input demand and marginal-cost functions. The primal approach starts with specifications for the production functions. For this study, we chose functional forms for the production functions that would lead to a homogeneous cost function in z_1 and z_2. Because the Cobb-Douglas specification meets this criterion, it was selected to specify the two production functions. The Cobb-Douglas production functions for quarterly fishing trips and fish catch are written as:

$$z_1 = (e)^{\alpha_{10}}(x_1)^{\alpha_{11}}(t_1)^{\alpha_{12}}(d)^{\alpha_{13}} \text{ ; and}$$

$$z_2 = (e)^{\alpha_{20}}(x_2)^{\alpha_{21}}(t_2)^{\alpha_{22}}(k)^{\alpha_{23}} \prod_{j=4}^{s} (a_j)^{\alpha_{2j}}$$

where:

$$e = (\ln)^{-1}1;$$

and the exogenous technology variables are defined as:

d = one-way distance to the given river;

k = depreciated present value of fishing equipment used on salmon and steelhead fishing trips (including tackle and special clothing); and

a_j = the j*th* site quality attribute, where j = 1,. . ., s.

All these variables serve as shifters of the production and marginal cost functions. The quality variables can be related to policy-controlled variables through a function such as,

$$a = a(S),$$

where S is a set of variables influenced directly by policy decisions.

To derive the commodity-demand equations, start with either a specification for the direct utility function (the primal approach) or a specification for the indirect utility function (the dual approach). There are advantages of choosing a flexible functional form for the indirect utility function; however, derivation of welfare estimates from commonly used flexible functional forms is not straightforward. Although the shortcomings of the Cobb-Douglas specification of the indirect utility function are well known, this specification does have the advantage of providing explicit functional forms for welfare measures. The Cobb-Douglas specification can also be regarded as a nonlinear approximation to the "true" utility function. We chose to use the Cobb-Douglas specification for the indirect utility function in this application, and it is written as:

$$U = (I/\pi_1)^{\gamma_1} \ (I/\pi_2)^{\gamma_2} \ (I/\pi_3)^{\gamma_3} \ ,$$

where I is implicit full income and π_1 and π_2 are the shadow prices for z_1 and z_2. The variable π_3 represents the shadow prices for all other m-2 commodities. All the m technologies are assumed homogeneous to the same degree in their respective commodities; hence, the variable I can be regarded as an exogenous variable.

Full income was calculated for each angler by adding the opportunity cost of the total amount of time available per quarter for household-production activities to the amount of available income per quarter. (Available income data were asked for in the questionnaires.) Twelve hours per day were assumed to be available for both work and household-production activities. The remaining 12 hours of each day were assumed to be spent in activities with zero opportunity cost. The opportunity cost of household-production time (w) was valued at one-third of the wage rate. This value was within the relevant range of one-fourth to one-half of the wage rate that is indicated by some empirical research (Cesario 1976).[6] Regular labor time was assumed to be fixed. The amount of time spent on steelhead fishing trips would thus be taken away from time that would otherwise be spent participating in other household-production activities rather than from time that would be spent at the angler's regular job.

Because wage-rate data were not asked for in the questionnaires, each angler's average wage rate was estimated by dividing total yearly household income (in 1977 dollars) by the number of hours spent working during the year. (Data on annual family income and on the mean number of hours spent working per week were requested.) Earned income for the respondent was estimated to be 80 percent of family income for those respondents working for pay during the given quarter. Those anglers not working for pay during the quarter were assigned an opportunity cost of zero.

Data on water-quality factors were obtained from various government agencies for only a subset of the sample rivers. Our original objective was to use a single variable to reflect catchable fish stocks in each river during each quarter. In addition, we planned to use physical water-quality measures expected to influence the catchability of steelhead (such as turbidity). Unfortunately, not much good data on fish populations in Oregon rivers are available. We decided that, for those rivers believed to support primarily hatchery fish, data on the numbers of smolts released from hatcheries could be used to construct a variable that would be a reasonably good substitute for adult fish stocks. Data on hatchery releases were acquired from the Oregon Department of Fish and Wildlife for eight of the rivers.

For those same eight rivers, data on daily streamflow (cubic feet per second) were from the Oregon Department of Water Resources. Monthly data on water temperature (degrees Celsius), turbidity (Jackson turbidity units), total nonfilterable residue (milligrams per liter), and dissolved oxygen were acquired from the U.S. Department of Environmental Quality. To construct water-quality variables for inclusion in the quarterly fish-catch production function, we averaged the quality data over the sampling locations along each river and over the days (or months) of each quarter.

---

[6] The choice of one-third of the wage rate as the opportunity cost of time was necessarily arbitrary. Theoretical arguments can be provided for other magnitudes or for not having the opportunity cost related to the wage rate. Recent empirical evidence by Smith and others (1983) concludes that ". . .the estimation of the multiple relating these opportunity costs to the wage rate is not a trivial task" (p. 276).

Because water-quality data were available for only a portion of the sample, two separate model specifications were developed. One model specification included the site-quality variables, and the other did not. The latter model specification could be estimated with the complete set of sample observations. The quarterly fish-catch production function for this model is written as:

$$z_2 = (e)^{\alpha_{20}}(x_2)^{\alpha_{21}}(t_2)^{\alpha_{22}}(k)^{\alpha_{23}}(e)^{\alpha_{24} q_1 + \alpha_{25} q_2 + \alpha_{26} q_3} ;$$

where: $q_i = 1$ if quarter i, 0 otherwise.

The coefficients of the dummy variables representing the first three quarters are assumed to pick up differences in environmental conditions during the year.

Estimated HP Model Excluding Policy-Related Variables

The model specification that excludes policy-related quality variables was used in this study to derive estimates of the mean value of a steelhead-fishing experience in Oregon. This model specification may be more useful than the one including policy-related variables for evaluating the benefits of steelhead fishing in Oregon because a larger sample covering more rivers is available. Also, because of the larger number of observations, advanced estimation techniques can be used to derive better estimates of the taste and technology parameters of this model specification.

By using the specifications for the production functions and the indirect utility function from the preceding section, we derived the system of demand equations for steelhead fishing-related inputs and commodities. If the two technologies are assumed to exhibit constant returns to scale (which implies that $\alpha_{11} + \alpha_{12} = 1$ and $\alpha_{21} + \alpha_{22} = 1$), then the demand equations are written as:

$$x_1 = \left(\frac{1-\alpha_{12}}{\alpha_{12}}\right)^{\alpha_{12}} (e)^{-\alpha_{10}} (z_1) (w)^{\alpha_{12}} (d)^{-\alpha_{13}} + (\varepsilon_1) ;$$

$$t_1 = \left(\frac{\alpha_{12}}{1-\alpha_{12}}\right)^{1-\alpha_{12}} (e)^{-\alpha_{10}} (z_1) (w)^{\alpha_{12}-1} (d)^{-\alpha_{13}} + (\varepsilon_2) ;$$

$$x_2 = \left(\frac{1-\alpha_{22}}{\alpha_{22}}\right)^{\alpha_{22}} (e)^{-(\alpha_{20} + \alpha_{24}q_1 + \alpha_{25}q_2 + \alpha_{26}q_3)} (z_2) (w)^{\alpha_{22}} (k)^{-\alpha_{23}} + (\varepsilon_3) ;$$

$$t_2 = \left(\frac{\alpha_{22}}{1-\alpha_{22}}\right)^{1-\alpha_{22}} (e)^{-(\alpha_{20} + \alpha_{24}q_1 + \alpha_{25}q_2 + \alpha_{26}q_3)} (z_2) (w)^{\alpha_{22}-1} (k)^{-\alpha_{23}} (\varepsilon^{-\mu_2}) + (\varepsilon_4) ;$$

$$z_1 = \left(\frac{\gamma_1}{\gamma_1+\gamma_2+\gamma_3}\right)\left(\frac{\mu}{\pi_1}\right) + (\varepsilon_5) ; \text{ and}$$

$$z_2 = \left(\frac{\gamma_2}{\gamma_1+\gamma_2+\gamma_3}\right)\left(\frac{\mu}{\pi_2}\right) + (\varepsilon_6) .$$

where $\varepsilon_1, \ldots, \varepsilon_6$ denote stochastic error terms.[7] A constant-returns-to-scale (CRS) technology seems reasonable for fishing trips; for a given distance, a doubling of travel expenditures and time would be expected to result in a doubling of the number of trips that can be taken. For the fish-catch technology, on the other hand, the assumption of CRS may or may not be reasonable. Earlier regression results obtained by estimating the two production functions suggested that the hypothesis of CRS could not be rejected for both the fishing trips and fish-catch technologies (see Strong 1983).[8] To use the full-income variable (μ) in the model, the other m-2 technologies must be assumed to be CRS as well.

Because π_1 and π_2 are unknowns in the model but are functions of known variables, the marginal-cost equations for z_1 and z_2 were substituted into the commodity-demand equations. The two marginal-cost equations are written as:

$$\pi_1 = (1-\alpha_{12})^{-(1-\alpha_{12})} \; (\alpha_{12})^{-\alpha_{12}} \; (e)^{-\alpha_{10}} \; (w)^{\alpha_{12}} \quad (d)^{-\alpha_{13}} \; ; \text{ and}$$

$$\pi_2 = (1-\alpha_{22})^{-(1-\alpha_{22})} \; (\alpha_{22})^{-\alpha_{22}} \; (e)^{-(\alpha_{20} + \alpha_{24}q_1 + \alpha_{25}q_2 + \alpha_{26}q_3)} \quad (w)^{\alpha_{22}} \; (k)^{-\alpha_{23}}$$

When these equations are substituted for π_1 and π_2, the resulting commodity-demand equations include both taste and technology parameters. These demand equations can be simplified by writing them as:

$$z_1 = \lambda_1(1-\alpha_{12})^{(1-\alpha_{12})} \; (\alpha_{12})^{\alpha_{12}} \; (e)^{\alpha_{10}} \; (w)^{-\alpha_{12}} \; (d)^{\alpha_{13}} \; (\mu) \; + \; (\varepsilon_5) \; ; \text{ and}$$

$$z_2 = \lambda_2(1-\alpha_{22})^{(1-\alpha_{22})} \; (\alpha_{22})^{\alpha_{22}} \; (e)^{(\alpha_{20} + \alpha_{24}q_1 + \alpha_{25}q_2 + \alpha_{26}q_3)} \; (w)^{-\alpha_{22}} \; (k)^{\alpha_{23}} \; (\mu) + (\varepsilon_6) \quad ;$$

where $\lambda_1 = \dfrac{\gamma_1}{\gamma_1+\gamma_2+\gamma_3}$ and $\lambda_2 = \dfrac{\gamma_2}{\gamma_1+\gamma_2+\gamma_3}$

Estimates for γ_1 and γ_2 were not required for welfare analysis in the z_1 and z_2 markets (shown below). For this study, estimates for λ_1 and λ_2 were sufficient.

A nonlinear regression technique can be used to simultaneously estimate the six demand equations. We used the three-stage least-squares (3SLS) procedure to obtain consistent and asymptotically efficient parameter estimates. Because 3SLS estimates are asymptotically and normally distributed, the 3SLS regression procedure can form the basis for statistical inference in nonlinear models (Berndt and others 1974). Gallant and Jorgenson (1979) discuss advantages of using a nonlinear 3SLS approach.

---

[7] The input demand equations were found by solving this problem: minimize $\mu = x_1 + wt_1 + x_2 + wt_2$ subject to $z_1 = F_1(x_1,t_1,d,\alpha_1)$ and $z_2 = F_2(x_2,t_2,k,q_1,q_2,q_3,\alpha_2)$. The commodity-demand equations were found by applying Roy's identity to the indirect utility function.

[8] A more reliable test of the CRS hypothesis could have been made if data had been available on total quarterly fish catch and total quarterly inputs.

Table 1—Results of nonlinear regression[a]

Parameter[b]	Estimate	Approximate standard error
a_{10}	2.6709	0.1411
a_{12} (t_1)	.4323	.0157
a_{13} (d)	-1.0622	.0290
a_{20}	-2.9100	.5967
a_{22} (t_2)	.9961	.0033
a_{23} (k)	.1345	.0779
a_{24} (q_1)	.7038	.4952
a_{25} (q_2)	-.0851	.5357
a_{26} (q_3)	.5170	.5388
λ_1 (π_1)	.0006	.0001
λ_2 (π_2)	.0062	.0010

[a] Number of observations = 300.

[b] The main variable each parameter is associated with is indicated in parentheses.

The parameter estimates obtained and their approximate standard errors are presented in table 1.[9] Although these standard errors are only approximations, they may give a clue as to which parameter estimates are statistically significant. According to these results, only three of the parameters—α_{24},α_{25}, and α_{26}—were not significant at the 90-percent probability level. These were the parameters on the quarterly dummy variables (q_1, q_2, q_3). As for the other parameter estimates that were statistically significant, the estimates for the parameters α_{12}, α_{13}, α_{22}, α_{23}, λ_1, and λ_2 seemed to have the correct signs. They also appeared to have fairly reasonable values, but no known a priori evidence existed to support these results. There was also no known a priori evidence to base hypotheses on for the other two statistically significant parameters (the constant terms α_{10} and α_{20}).

These results suggested that the composite transportation input, x_1, had a slightly higher output elasticity (0.43) than did the travel-time input, t_1 (0.57 = 1 - 0.43). The results also suggested that the output elasticity for the fishing-time input, t_2, was not significantly less than unity (0.996), which suggests that the composite-fishing input, x_2, had virtually no impact on the number of fish caught. Indeed, only half of the sample of 300 anglers had a nonzero value for the variable x_2.

[9] The 300 observations comprise the subset of the sample for which the variables w, d, and k were greater than zero. We had to drop those observations for which any one or more of these three variables was zero because all these variables appeared in the denominator of at least one equation in the demand system.

The results show (table 1) that the first quarter was the best of the four quarters for steelhead fishing, followed by the third, fourth, and second quarters. Probably no significant differences existed among the quarters in the efficiency of producing sport-caught fish; the apparent statistical insignificance of the estimates for α_{24}, α_{25}, and α_{26} bears this out. Perhaps using intervals other than quarters would have been more appropriate for determining differences in fishing success rates over the year.

The parameter estimates in table 1 can be used to derive estimates of the value of steelhead fishing for exact welfare measures. Two generally accepted welfare measures of benefits to an individual from a policy change are compensating variation and equivalent variation. Compensating variation represents the maximum amount of money an individual is willing to pay for a policy change. Equivalent variation represents the minimum amount of money the individual is willing to accept in lieu of a policy change. Because taking trips and catching fish are both assumed to be utility-yielding components of the fishing experience, the benefits derived from a fishing experience are determined through the simultaneous estimation of benefits in both of these commodity markets.

In measuring total recreational benefits for an angler, we were interested in estimating the compensating variation (CV) for an increase in shadow prices from their current levels (π_1^0, π_2^0) to the minimum levels at which the demand for both z_1 and z_2 is reduced to zero (π_1^*, π_2^*). The negative of CV represents the minimum amount of money an angler requires as compensation for agreeing not to go steelhead fishing. A formula for quarterly compensating variation is found by solving for CV:[10]

$$V(\pi_1^0, \pi_2^0, \pi_3^0, \mu^0, \gamma) = V(\pi_1^*, \pi_2^*, \pi_3^0, \mu^0 - CV, \gamma) .$$

Because shadow prices are not known but are estimated by using marginal cost functions, a more accurate procedure for evaluating recreation benefits might be to determine the welfare impacts of price changes in the input markets using known input prices.

By using results in Just and others (1982) for welfare measurement in input space, we showed that total recreational-benefit estimates can be determined by sequentially evaluating total welfare impacts across all input markets. If a necessary input exists for a given commodity, then the total welfare impact is equal to the compensating variation for an increase in the price of the necessary input to its shutdown level.[11]

---

[10] To simplify the discussion, all benefit measures were defined in terms of compensating variation, although the empirical results for both compensating and equivalent variations are presented. The negative of equivalent variation (EV) represented the maximum amount of money the angler would pay to avoid the prices at which fishing would no longer be affordable. Solve the equation for EV:

$$V(\pi_1^0, \pi_2^0, \pi_3^0, \mu^0 + EV, \gamma) = V(\pi_1^*, \pi_2^*, \pi_3^0, \mu^0, \gamma) .$$

[11] The shutdown price for a necessary input is the minimum price that would induce the household to stop producing the commodity.

In this study, two variables for time input, t_1 and t_2, were necessary to produce z_1 and z_2, respectively. Consequently, total recreational benefits were calculated by determining the value of compensating variation for a simultaneous change in w in both input markets from the current level of w (w_0) to the levels at which the demand for each input were just reduced to zero (w_1^*, w_2^*). At the opportunity costs w_1^* and w_2^*, the angler would cease production (and hence consumption) of both z_1 and z_2. Thus, the value of compensating variation for an increase in the opportunity costs to their shutdown levels gave the welfare impact of eliminating z_1 and z_2 from the angler's choice set, or equivalently, from pricing the angler out of the markets for z_1 and z_2.

Given the implied, indirect utility function in input space and the parameter estimates from the preceding section, the estimated value of compensating variation for a given angler is equal to:

$$CV = \mu^0 - (w_1^*/w^0)^{\alpha_{12}(\lambda_1)} \; (w_2^*/w^0)^{\alpha_{22}(\lambda_2)} - (\mu^0) \; ,$$

$$= \mu^0 - (w_1^*/w^0)^{0.4323(0.0006)} \; (w_2^*/w^0)^{0.9961(0.0062)} \; (\mu^0) \; , \text{ or}$$

$$= \mu^0 - (w_1^*/w^0)^{0.00026} \; (w_2^*/w^0)^{0.00617} \; (\mu^0) \; .$$

The welfare impacts in a single commodity market can be determined by calculating the compensating variation for a price change from w^0 to the shutdown price in the corresponding, necessary input market; for example, the estimated value of compensating variation in the z_1 market is equal to:

$$CV_1 = \mu^0 - (w_1^*/w^0)^{0.00026} \; (\mu^0) \; .$$

In the z_2 market, the estimated value of compensating variation is equal to:

$$CV_2 = \mu^0 - (w_2^*/w^0)^{0.00617} \; (\mu^0) \; .$$

In this application, the demand curves for t_1 and t_2 were asymptotic to both axes—so we could not determine shutdown prices by finding the points on the demand curves where the quantities demanded of t_1 and t_2 were just reduced to zero. As an alternative, we assumed that the maximum value of w in the sample can serve as a reasonable estimate for both w_1^* and w_2^* for all anglers. The fact that no angler in the sample had an opportunity cost greater than the sample maximum implied that the probability of an angler with an opportunity cost greater than this value going steelhead fishing was extremely small.

Because both shutdown prices were assumed to be equivalent ($w_1^* = w_2^*$), the formula for the total value of compensating variation for the angler was simplified to:

$$CV = \mu^0 - (w^*/w^0)^{0.00026 + 0.00617} \; (\mu^0) \; , \text{ or}$$

$$= \mu^0 - (w^*/w^0)^{0.00643} \; (\mu^0) \; .$$

Table 2—Estimates of per-unit values for a representative steelhead angler

Commodity	Value per unit: Compensating variation	Value per unit: Equivalent variation
	Dollars	
Fishing experience	21.57	21.25
Fishing trip	.86	.86
Sport-caught fish	25.61	25.25

This formula gives an estimate of the compensating variation on a quarterly basis. The estimates of the value of a fishing experience for a representative angler are shown in the first column of table 2. This was done by using the sample mean values of the variables w and μ in the formula for CV and dividing CV by the sample mean value of z_1. Table 2 also gives the estimated values of a fishing trip and of a sport-caught fish for a representative angler. Each of these values was derived by calculating $CV_1(CV_2)$ for a representative angler and dividing the result by the sample mean value of $z_1(z_2)$.

Of all the per-unit value estimates, probably the most useful is the estimated value of a fishing experience. This value can be used to determine the welfare effects of a change in the number of steelhead fishing trips taken assuming no change will occur in the mean number of fish caught per trip.

The estimated value of a sport-caught fish can be used to determine the welfare effects of a change in total fish catch not induced by a change in the total number of fishing trips taken. This value represents the amount anglers are willing to pay for the right to catch a fish, given that they have exercised their right to visit the site. One place where this value can be used is in a proposed policy-induced change in fish stocks, which would be expected to have some predicted effect on fish catch. One problem with this is predicting the actual effects of changes in fish population on fish catch.

A problem with using any of these value estimates is that they are based on an all-or-none concept; that is, they are computed by estimating the welfare effects of reducing demand to zero. The validity of using these mean values to evaluate the benefits of marginal changes in demand is questionable. Because fishing trips and sport-caught fish are endogenous variables in this framework, marginal values of these commodities cannot be derived from the model presented in this chapter. This model is designed to estimate instead the welfare effects of changes in exogenous variables.

Estimated HP Model Including Policy-Related Variables

Empirical results for the HP model specification including policy-related variables were estimated by using the observations for which quality data were available. Because of the relatively small sample used for this analysis, an estimation technique different from that used in the previous section was necessary to estimate the taste and technology parameters. A two-stage procedure was used wherein the technology parameters were estimated in the first stage and conditional taste parameters were estimated in the second.

To obtain technology-parameter estimates, the ordinary least-squares regression procedure was applied to the two production functions for quarterly fishing trips (z_1) and quarterly fish catch (z_2). They are specified in Cobb-Douglas form as:

$$z_1 = (e)^{\alpha_{10}} (x_1)^{\alpha_{11}} (t_1)^{\alpha_{12}} (e)^{\alpha_{13}d_1+\alpha_{14}d_2+\alpha_{15}d_3+\mu_1}, \text{ and}$$

$$z_2 = (e)^{\alpha_{20}} (x_2)^{\alpha_{21}} (t_2)^{\alpha_{22}} (k)^{\alpha_{23}} (Rel)^{\theta_1} (Sf)^{\theta_2} (Temp)^{\theta_3} (Turb)^{\theta_4} (Res)^{\theta_5} (e)^{\mu_2};$$

where the input variables x_1, t_1, x_2, and t_2 are defined as before: x_1 is transportation inputs, t_1 is travel time, x_2 is fishing inputs, and t_2 is fishing time; u_1 and u_2 are random-error terms. The exogenous quality variables included in the z_2 production function were lagged smolt releases (Rel), streamflow (Sf), temperature (Temp), turbidity (Turb), and total nonfilterable residue (Res). These quality variables were believed to influence either adult fish populations or the catchability of fish.[12]

In the z_1 production function, the distance variable d from the model specification used earlier has been replaced with three dummy variables defined as:

$$d_1 = \begin{cases} 1 \text{ if distance to river is less than 30 miles,} \\ 0 \text{ otherwise;} \end{cases}$$

$$d_2 = \begin{cases} 1 \text{ if distance to river is between 30 and 60 miles,} \\ 0 \text{ otherwise; and} \end{cases}$$

$$d_3 = \begin{cases} 1 \text{ if distance to river is between 60 and 90 miles,} \\ 0 \text{ otherwise.} \end{cases}$$

These dummy variables were used because a specification bias might have resulted if d had been used instead.[13]

Another possible specification bias exists in the z_1 production function as a result of constructing the variables x_1 and t_1 by multiplying both average travel time and average input expenditures per trip by the number of trips taken quarterly (z_1). This procedure can lead to a violation of the condition that the error term of the equation for z_1 is uncorrelated with any errors in the explanatory variables x_1 and t_1. Application of a simultaneous equation-estimation procedure (such as the three-stage least-squares procedure) should alleviate the problem of possible biases in the parameter estimates.

---

[12] Although dissolved oxygen is an important element of the steelhead habitat, insufficient variability in concentrations of dissolved oxygen occurred across the sample rivers during 1977 to estimate the effects on fish catch.

[13] It can be shown that the relationship between the variable t_1 and d can lead to biased parameter estimates if the z_1 production function including the variable d were estimated. The variable t_1 is constructed by using the formula:

$$t_1 = \frac{2(d)}{MPH} (z_1);$$

where MPH is travel speed in miles per hour.

To obtain technology-parameter estimates for this specification of the HP model, we estimated each production function in its logarithmic form by applying the ordinary least-squares regression procedure.

The estimated z_1 production function is written in logarithmic form as:

$$\ln(z_1) = \underset{(0.08991)}{-2.24702} + \underset{(0.08355)}{2.36331(d_1)} + \underset{(0.08951)}{1.19280(d_2)} + \underset{(0.10014)}{0.65843(d_3)}$$

$$+ \underset{(0.04431)}{0.17610(\ln(x_1))} + 0.82390(\ln(t_1)) \quad (n = 374)^{14}\ R^2 = 0.76 .$$

In this chapter, R^2 is the proportion of variation in the mean-corrected dependent variable explained by regression. Numbers in parentheses are standard errors of the coefficients. All coefficients are significant at the 0.5-percent level. Although the hypothesis of CRS can be rejected at the 1-percent level (but not at the 0.5-percent level), CRS was imposed on this model. We hypothesized that the reason CRS can be rejected for a given distance zone (that is, d_1, d_2, or d_3) is that distance, and hence production efficiency, changes along the production curve for that zone. For a given distance, on the other hand, we assumed that the technology for the z_1 commodity would be CRS. We therefore assumed that the above model (in which α_{11} and $\alpha_{12} = 1$) describes production relationships for an average distance in each zone.

The estimating form for the fish-catch production function is given by:

$$\ln(z_2) = \alpha_{20} + \alpha_{21}\ln(x_2) + \alpha_{22}\ln(t_2) + \alpha_{23}\ln(k) + \theta_1\ln(\text{Rel}) + \theta_2\ln(\text{Sf}) + \theta_3\ln(\text{Temp}) + \theta_4\ln(\text{Turb}) + \theta_5\ln(\text{Res}) + u_2 .$$

The results from estimating this equation suggested that all the exogenous quality variables cannot be included together in the model, apparently because of high intercorrelations. These intercorrelations suggested that a serious multicollinearity problem exists in the model; moreover, of the five quality variables, only Rel had significant explanatory power. Not only were the coefficients to the other quality variables statistically insignificant, but some of them also seemed to have incorrect signs.

When each of the exogenous quality variables were included separately in the model, both Temp and Sf, besides Rel, had significant coefficients with the correct signs. But when these three variables were included together in the model, only Rel had a significant coefficient, and the coefficient to Sf seemed to have an incorrect sign. Because Rel, Temp, and Sf could not be included together in the model according to these results, the three possible pairs of these variables were tested.

---

[14] This portion of the sample included those 374 observations for which $x_1,t_1 = 0$. Estimation of the Cobb-Douglas production function by using ordinary least squares required nonzero values for all variables.

Only the Temp-Sf pair seemed to work well in the model. Two different specifications for the z_2 production function are therefore acceptable statistically. In one, the variable Rel is included; in the other, both Temp and Sf are included. The two alternative estimated production functions are written as:

$$\ln(z_2) = \underset{(1.3568)}{-5.17045} + \underset{(0.08960)}{0.27729}(\ln(x_2)) + 0.72271(\ln(t_2))$$

$$+ \underset{(0.09562)}{0.04163}(\ln(k)) + \underset{(0.11526)}{0.31599}(\ln(Rel)) \quad (n = 34) \quad R^2 = 0.40; \text{ and,} \quad (1)$$

$$\ln(z_2) = \underset{(0.10124)}{0.27859}(\ln(x_2)) + 0.72141(\ln(t_2)) + \underset{(0.11322)}{0.06292}(\ln(k))$$

$$- \underset{(0.39218)}{1.05698}(\ln(Temp)) + \underset{(0.12219)}{0.05550}(\ln(Sf)) \qquad (n = 31).^{15} \quad (2)$$

Given the above technology-parameter estimates, conditional taste-parameter estimates are determined by means of the ordinary least-squares regression procedure, which is used to estimate each commodity demand equation. The forms of the two commodity demand equations are written as:

$$z_1 = \lambda_1 \frac{\mu}{\pi_1} + e_1 \text{ , and}$$

$$z_2 = \lambda_2 \frac{\mu}{\pi_{21}} + e_2 \text{ ;}$$

where π_1 is the estimated value of the implicit price of z_1, and π_{21} is the estimated value of the implicit price of z_2. Both e_1 and e_2 are random error terms. The variable π_{21} was derived from the estimated z_2 production function in which the lagged smolt-releases variable was included.

Each set of taste parameter estimates shown in table 3 corresponds to a different definition for w.[16] These estimates can be used along with the technology-parameter

[15] The observations used to estimate each production-function specification were those portions of the complete sample of observations for which quality data were available and $z_2, x_2, k > 0$. Less than one-fourth of the complete sample both caught fish and used market fishing inputs, and quality data were available for only one-third of that subsample. Deleting the observations for which $z_2, x_2, k = 0$ led to biased parameter estimates; but more advanced procedures allowing inclusion of these observations were not applicable because of the small sample sizes.

[16] Because a zero opportunity cost yields implicit prices of zero, and because each implicit price is the denominator of the respective commodity demand equation, the observations where $w_1 = 0$ were dropped from the sample for estimating λ_1 and λ_2. The z_1 demand equation was fitted with the 292 observations from the total 404 where $w_1 > 0$. The z_2 demand equation was fitted with the 40 observations where $w_1 > 0$ and data on smolt releases were available.

Table 3—Estimates of taste parameter

Opportunity cost of time	λ_1	λ_2
1/4 hourly income	0.00245	0.01279
	(.00016)	(.00377)
1/2 hourly income	.00358	.01837
	(.00023)	(.00511)

Note: Numbers in parentheses are standard errors.

estimates to calculate the welfare effects of exogenous quality changes. For a change in smolt releases from Rel^0 to Rel^1, for example, the estimated value of compensating variation per quarter is equal to:

$$CV_1 = \mu^0 - (\pi_{21}^1/\pi_{21}^0)^{\lambda_2} (\mu^0) ;$$

$$\text{where } \pi_{21}^r = 317.6094(w_1^0)^{0.72271} (k_1^0)^{-0.04163} (Rel^r)^{-0.31599}$$

and r = 1, 0. Similarly, the estimated compensating variation for a simultaneous change in streamflow and temperature from (Sf^0, $Temp^0$) to (Sf^1, $Temp^1$) is equal to:

$$CV_2 = \mu^0 - (\pi_{22}^1/\pi_{22}^0)^{\lambda_2} (\mu^0) ;$$

$$\text{where, } \pi_{22}^r = 1.8069(w^0)^{0.72141} (k^0)^{-0.06293} (Temp^r)^{1.05698} (Sf^r)^{-0.05550} .$$

With the Cobb-Douglas model specification, the demand for z_1 was not responsive to quality-induced changes in π_2. Consequently, quality-induced changes in the value of a fishing experience were determined by dividing the estimated quarterly welfare changes by the constant number of trips taken per quarter (z_1^0). Quality-induced changes in the demand for z_2 were determined by using the ordinary demand equation for z_2 in which the estimated implicit price equation with the appropriate quality variables included was substituted for π_2.

We tested the sensitivity of angler benefits and fish-catch rates to quality improvements. Table 4 shows estimates of the percentage increases in mean values per fishing experience and in mean numbers of fish caught per quarter for a 10-percent increase in smolt releases and for a simultaneous 10-percent decrease in water temperature and 10-percent increase in streamflow. The changes in values per visit were the means of changes in compensating and equivalent variations. The variables w, z_1, k, μ, Rel^0, $Temp^0$, and Sf^0 were fixed at their sample mean values to calculate the results shown in table 4. Accordingly, the results are for a representative river and a representative angler and suggest that a 10-percent improvement in water quality induces, on average, slightly more than a 1-percent increase in both benefits and fish-catch rates.

The HP framework can potentially be integrated with any forest-planning model predicting management-induced quality changes. The two HP model specifications presented empirically in this paper do not appear, unfortunately, to be completely compatible with currently available forest-management models.

Table 4—Estimates of the percentage change in the value of a fishing experience and the number of fish caught as a result of improvements in site quality of a representative river

Opportunity cost of time	10-percent increase in Rel		10-percent decrease in temp and increase in SF	
	Change in mean value per visit	Change in quarterly fish catch	Change in mean value per visit	Change in quarterly fish catch
	Percent			
1/4 hourly income	1.02	1.05	1.09	1.19
1/2 hourly income	1.02	1.05	1.09	1.21

The first model specification (in which a variable for lagged smolt releases was included) described lagged effects of quality changes on quarterly fish catch. This model can be used to evaluate benefits to steelhead anglers from changes in smolt release from hatcheries. In a forest-management context, perhaps this model could be useful for evaluating the welfare effects on steelhead anglers of management-induced changes in smolt stocks, but only if the effects of changes in smolt production on fish catch are assumed to be similar to the effects of changes in smolt releases. To use the model in forest-management planning or policy analysis, users must assume that mortality rates and migration patterns are similar for wild and hatchery steelhead. Given this assumption, the HP model can be integrated with any forest-management model able to predict the effects of forestry practices on smolt production in given forest streams. Of course, a variable for total fish population in the model is preferable to a variable representing only hatchery fish.

The second specification of the HP model (in which both water temperature and streamflow variables were included) described the immediate effects of water-quality changes on fish catch per quarter. Although this model may be more compatible with current forest-management models, the immediate effects of quality changes on fish-catch rates are probably not as significant as are the lagged effects because young fish are generally more susceptible to changes in water quality than are adult fish.

One problem with both of the alternative model specifications was that some relevant quality variables were not included, either because of a lack of data or because of multicollinearity problems resulting from intercorrelations among the quality variables. The problem of omitted variables led to a specification bias in the parameter estimates. A possible remedy for the multicollinearity problem might be to use a general habitat-quality index composed of some combination (such as weighted average) of all the important quality parameters.

Summary

We have presented the empirical results from an application of Bockstael and McConnell's (1981) HP framework to 1977 data for steelhead sport fishing in Oregon. The framework provided a way to determine the benefits anglers derive from a fishing experience, which are defined as the benefits simultaneously derived from taking the fishing trip and from catching fish. Two nonmarket goods—the number of fishing trips taken and the number of sport-caught fish—were recognized in this model as utility-yielding components of sport-fishing experiences. Both of these commodities were "produced" by the anglers through use of various combinations of market goods and time inputs under a given set of environmental (technological) conditions.

The major distinction between this framework and other recreation valuation techniques was that fish catch was treated endogenously rather than exogenously. This allowed us to include water-quality variables, which can be related to policy-controlled variables, in the model as determinants of fish catch. The HP framework is thus potentially useful for evaluating the benefits of policy-induced quality changes.

Two different specifications of the steelhead fishing HP model were estimated. The first specification does not include policy-related quality variables and was empirically estimated with observations from 29 rivers in Oregon. A nonlinear, three-stage, least-squares procedure was applied to the complete system of structural demand equations to obtain estimates of both taste and technology parameters. These parameter estimates were used to derive estimates of the mean values of a fishing experience in terms of both compensating and equivalent variation. Mean values were also obtained for a fishing trip and for a sport-caught fish by calculating benefits separately in each commodity market. It is arguable whether these mean values of a sport-caught fish would be useful for evaluating marginal changes in fish catch because fish catch was an endogenous variable in this model.

The second model specification included policy-related quality variables and was used to determine the welfare effects of exogenous quality changes influencing fish catch. Because quality data were not readily available for all the sample rivers, this model specification was estimated with data for only eight rivers. A single-equation estimation procedure was used to obtain parameter estimates in two stages. In the first stage, technology-parameter estimates were obtained by applying ordinary least squares to the production functions for fishing trips and fish catch. In the second stage, ordinary least squares was applied to the two commodity-demand equations to derive taste-parameter estimates conditioned on the predetermined technology-parameter estimates. These parameters were used to derive estimates of the compensating and equivalent variations associated with a hypothetical improvement in water quality. Unfortunately, multicollinearity problems prevented the inclusion in the model of all the quality variables at one time. Despite a possible specification bias resulting from omitted variables, these results demonstrated the potential usefulness of the HP framework for analyzing policy changes that will influence the quality of fishing streams in Oregon.

Literature Cited

Barnett, William A. 1977. Pollak and Wachter on the household production function approach. Journal of Political Economy. 85(5): 1073-1082.

Becker, Gary S. 1965. A theory of the allocation of time. Economic Journal. November; 75: 493-517.

Berndt, Ernest R.; Hall, B.H.; Hall, Robert E.; Hausman, Jerry A. 1974. Estimation and inference in nonlinear structural models. Annals of Economic and Social Measurement. 3: 653-665.

Bockstael, Nancy E.; McConnell, Kenneth E. 1981. Theory and estimation of the household production function for wildlife recreation. Journal of Environmental Economics and Management. 8: 199-214.

Cesario, Frank J. 1976. Value of time in recreation benefit studies. Land Economics. 52(1): 32-41.

Gallant, A. Ronald; Jorgenson, Dale W. 1979. Statistical inference for a system of simultaneous, nonlinear, implicit equations in the context of instrumental variable estimation. Journal of Econometrics. 11: 275-302.

Just, Richard E.; Hueth, Darrell L.; Schmitz, Andrew. 1982. Applied welfare economics and public policy. Englewood Cliffs, NJ: Prentice-Hall, Inc. 41 p.

Michael, Robert T.; Becker, Gary S. 1973. On the new theory of consumer behavior. Swedish Journal of Economics. 75: 378-396.

Pollak, Robert A.; Wachter, Michael L. 1975. The relevance of the household production function and its implications for the allocation of time. Journal of Political Economy. 83(2): 255-277.

Pollak, Robert A.; Wachter, Michael L. 1977. Reply: Pollak and Wachter on the household production approach. Journal of Political Economy. 85(5): 1083-1086.

Smith, V. Kerry; Descousges, William H.; McGioney, Matthew P. 1983. The opportunity cost of travel time in recreation demand models. Land Economics. 59(3): 259-278.

Strong, Elizabeth J. 1983. A note on the functional form of travel cost models with zones of unequal populations. Land Economics. 59(3): 342-349.

Chapter 7: Valuing Oregon Salmon by Using a Multimarket, Hedonic Travel-Cost Method

Gardner Brown, Jr.[1,2]

The travel-cost method has been used for years to estimate the value of recreational sites. The driving force behind this method is that people from different origins bear different travel costs to reach a common site. They can therefore be expected to participate at different rates. Two features of this method need to be mentioned. First, the method captures an all-or-none value for the site; that is, it does not provide information about the marginal value of changing the site a little bit by improving its quality in some fashion. Second, in practice, the procedure assumes that all recreationists have the same opportunities to enjoy substitute locations at the same price; substitutions are therefore omitted from the analysis. Omitting substitutes when they in fact exist overestimates the value of improvements at a site and underestimates the loss from quality changes at a site.

---

[1] GARDNER BROWN, Jr., is professor, University of Washington, Department of Economics, Seattle, WA 98195.

[2] Research assistance was provided by Ching-Kai Hsiao.

Fortunately, including substitutes in the analysis solves the second problem and also responds to the first problem. Burt and Brewer (1971) were the first to generalize the travel-cost method to many sites, and their study is the point of departure for the analysis below. But, in contrast to Burt and Brewer who assume sites differ only in location, I have included the location and the quality of the sites, the latter measured by expected fishing success at sites.

The Hedonic Travel-Cost Method

I assumed that each recreation site has a bundle of characteristics. Consumers from a given origin, by paying to travel a bit further, can obtain a richer bundle of characteristics. Thus, in the first step of the analysis, the implicit price of one more unit of a characteristic was estimated by a hedonic price equation. This step is the opposite of applying the usual travel-cost method, which features one site attracting visitors from many origins. I picked one origin and estimated the cost of reaching different sites. The derivative of the hedonic price function with respect to each site characteristic from this first-stage regression yielded the implicit price of each characteristic for that market (origin). Because people from different origins (markets) face different opportunities, each time this first step is repeated for a different origin it provides a new set of implicit prices for the characteristics.

In the second stage, the quantity of characteristics each recreationist enjoys was regressed on the estimated implicit prices of the characteristics and other demand determinants, such as income and age. This step yielded a demand curve for each characteristic from which the marginal value of a characteristic was computed.

Put more formally, I assumed that the consumer's evaluation of the quality of sites depends on objectively measurable characteristics. The characteristics (Z_1) of sites, the number of trips taken (N), and all other goods (X) enter the representative individual's quasi-concave utility function:

$$U = U(Z_1, \ldots, Z_n, N, X) .$$

The total private cost of using different sites differs by location even if user fees are not charged. The further the recreation site from the resident, the greater the out-of-pocket costs of getting to the site. The slower the travel, the greater the time costs of the site. The price of the *ith* site providing a vector of characteristics, Z, was the sum of entry fees, f(Z), and travel costs (both time and money costs), T(Z), plus the fixed cost of the trip, a (that is, those costs not changing with quality). The fixed cost was assumed to be invariant to the site chosen.[3] The total cost or price per trip is:

$$V(Z) = a + f(Z) + T(Z) . \qquad (1)$$

The budget constraint facing the individual therefore is:

$$M = X + N \cdot V(Z) ; \qquad (2)$$

[3] Implicitly, I assumed that auxiliary goods, such as food and lodging purchased at the site, are constant with respect to characteristics. If the cost of these facilities does consistently differ with characteristics, then the fixed cost of a trip of given length should also be a function of characteristics.

where M is income and X is assumed to have a unitary price. Utility maximization subject to the budget constraint yields the following first-order conditions:

$$U_{Z_i} - \lambda N(f_{Z_i} + T_{Z_i}) = 0 , \quad (i-1,. . ., n) \tag{3}$$

$$U_N - \lambda V(Z) = 0 , \text{ and}$$

$$U_X - \lambda S = 0 ;$$

where λ is the Lagrangian function associated with (2) and is interpreted as the marginal utility of income.

The sum,

$$f_{Z_i} + T_{Z_i} = \partial V/Z_i ,$$

is the marginal price of characteristic Z_i per trip.

The consumer's choice of outdoor recreation, expressed in terms of two simultaneous demand equations, was obtained by combining equations (2) and (3) to give:

$$Z_i = g(f_{Z_i} + T_{Z_i},N,W) \quad (i=1,. . ., n) , \text{ and} \tag{4}$$

$$N = h(V(Z),Z,W) ; \tag{5}$$

where W is a vector of exogenous demand-shift variables, including M. V(Z), the cost of a trip (from equation 5), can be expressed in terms of its component parts.[4] Thus, when the prices are constant, equation (5) can also be expressed as:

$$N = t(f_Z + T_Z,a,Z,M) . \tag{5a}$$

The supply of trips to each origin was assumed to be perfectly elastic; that is, the cost of a second trip to any site was the same as the cost for the first trip. The supply of characteristics at each site was assumed to be fixed (unresponsive to prices) by exogenous factors.

Explicit information was available for the empirical study below on only one relevant site characteristic, fishing success. The intercept term of the first-stage regression picked up the mean effect of the omitted characteristics and was used as a proxy for the price of other characteristics. Because no measure of quantity existed for the omitted characteristic, its demand equation was not estimated. Thus, only two equations were estimated, one for trips and the other for success. The missing data on other characteristics causes a bias in the parameter for success except when the independent variables truly are statistically independent (this is unlikely to occur).

---

[4] The more frequently used specifications for the demand equations (4) and (5) are:

$$Z_i = Z_i(f_{Z_i} + T_{Z_i} , V(Z),W) , \text{ and} \tag{4.1}$$

$$N = N(f_{Z_i} + T_{Z_i} , V(Z),W) . \tag{5.1}$$

Solving (5.1) for V(Z) and substituting into (4.1) yields (4); likewise, solving (4.1) for f_{Z_i} and T_{Z_i} and substituting in (5.1) yields (5), if it is assumed these functions exist.

Data and Variables

Data

The questionnaires the basic data were drawn from were described in detail elsewhere (see appendix to chapter 1). In brief, a sample of 9,000 was drawn from purchasers of Oregon angling licenses in 1977. The sample was about 1.5 percent of the total angler licenses purchased. Questionnaires were mailed to about 1,200 anglers in the first and last quarters of the calendar year; about twice and three times that number received questionnaires in the second and third quarters, respectively. Just under one-half of the returned questionnaires were usable; a much smaller number of respondents (405) were primarily interested in salmon fishing, and not all responded to questions critical for the analysis. The sample was further reduced to 290 because a minimum number of responses were needed from a given origin; this was necessary to run a first-stage regression, from which the implicit prices were obtained. The minimum acceptable number of observations from any county was arbitrarily set at 5, which limited the study to 14 counties; that is, 14 prices.

Variables

The variables in the model (with their abbreviations in parentheses) were defined as follows:

Distance (AVDN)—The reported round-trip distances from any given county to any given salmon-fishing location (county or site) were averaged across respondents going to the same fishing site to provide an estimate of distance.

Success per hour (DST)—Respondents reported success and effort in the questionnaire. From these responses, the catch at each site per unit of effort was estimated. This was used as the measure of site quality. Success at a site will vary for people of equal fishing skill. People select a fishing site based, in part, on expectations, which I took to be the sample mean of success per hour fished. The actual success of an angler was therefore regarded as the true value plus random variation. Ideally, a site input characteristic, such as fish density, is a more objective variable to use, but this was not available.

Success per hour (ASE)—This is the average catch per hour (DST) aggregated across the sum of the trips taken by an individual to different sites. Each individual in the sample has an ASE.

Initially, I computed the success of an area for other species of fish because I thought this might be a valuable characteristic. The other species were either insignificant or, for steelhead, very highly correlated with salmon success rates, so they were dropped from the analysis.

Trips (N)—Individuals provided the number of times they went salmon fishing during the quarter they were sampled for. An estimate of the number of salmon-fishing trips per year would have been desirable. There may not be much error because 80 percent of the trips were taken during July and August, the period used for this analysis.

Income (INC)—The questionnaire asked respondents to check the income range of the total gross income for their family. The midpoint of each range was used to value INC.

Mileage costs—The first-stage regression estimated prices measured in miles (actually, marginal miles). Under some conditions, the second-stage demand function could be estimated in terms of miles and finally expressed in more conventional dollar terms. Earlier analysis of the data explicitly recognized that recreationists travel in a variety of vehicles, some with low gas mileage and some with high gas mileage. Thus the price of miles differs for individuals. I used the cost-per-mile estimates from the U.S. Department of Transportation:[5]

Autos and pickups	9.75¢/mile
Motor homes and campers	11.60¢/mile

Time cost—Even though most economists agree that the opportunity cost of travel time is a relevant concept, neither a consensus nor a theoretically defensible empirical estimate of the opportunity cost of time during a trip to a recreation site exists. The controversy over the issue is easily accessible elsewhere and will not be discussed here. A basic estimate of time cost is found by estimating a wage rate on the strong assumption that all reported income is earned and further that each respondent works 2,000 hours per year. The wage rate ($/hour) can be transformed into a mileage cost ($/mile), given the rate of travel (miles/hour)—40 or 35 miles/hour if travel is by auto or camper, respectively—and an assumption about what fraction the opportunity cost of time is of the wage rate. This fraction is assumed to be 30 percent of the gross wage, which is on the order of 50 percent of the wage after taxes.

Entry fee (f)—I assumed that higher access costs were associated with higher quality sites, particularly because sea-going charter boats generally provide better quality fishing. The reported costs of guide service, equipment rental, boat launching fees, and fuel represented the entry fee for a site.

Age was tried as an explanatory variable in the demand equations, but it was never significant so it was dropped.

Estimation

In the first-stage regression, equation (1) was run in linear form for each of the 14 counties having five or more anglers in the sample. An illustrative regression for salmon anglers in Washington County is:[6]

$$\text{distance (AVDN)} = \underset{(3.10)}{50} + \underset{(5.49)}{247}\ \text{success per trip (DST)} \quad \bar{r}^2 = 0.74 . \qquad (6)$$

[5] Unpublished Report, 1976, "Cost of Owning and Operating an Automobile," U.S. Department of Transportation, Federal Highway Administration, Highway Statistics Division, Washington, DC.

[6] The original regression was run in units of catch per hour. The equation was converted to catch per trip based on hours÷trips = 3.45.

In this chapter, $\bar{R}^2$ and $\bar{r}^2$ are the proportion of variation in the mean-corrected dependent variable explained by the regression when corrected for degrees of freedom. Numbers in parentheses are t-statistics. The interpretation of equation (6) is that for a 20-percent increase in success per trip, from 0.30 to 0.36, a salmon angler must be willing to drive 15 more miles:

$$(\Delta \text{ distance} = 247 \cdot \Delta \text{ catch per trip}).$$

In general, nine of the slope or implicit price coefficients were positive (as they should be), and six of those had t-values greater than 1.85. Five had negative slope coefficients, of which only one was statistically significant. All intercept coefficients were positive, and six were statistically significant (t-values greater than 1.85). These results were not particularly good because the original study was designed to collect data for a different purpose than applying the hedonic travel-cost method.

Appropriate data for this type of study are economically acquired by cluster sampling around a significant number of origins. In the first stage, representative hedonic price functions for given groups of people are sought. Each group faces the same market prices; that is, the distance to an expected quality is the same for all members of the group.

I experimented with nonlinear representations of equation (1) by using squared terms for the independent variable, but these did not fit any better, although a couple of exceptions occurred. The coefficient for catch per trip obtained from the first-stage regression provided the implicit prices of catch per trip for each of the 14 counties in the regression. The value of zero was substituted for negative implicit prices on the assumption that zero is a better estimate of the marginal price of success than is a negative value. The constant term in each of the regressions represented the mean price in miles of the omitted characteristics.

In the second-stage regression, the catch per trip at the site where each individual fished was regressed on the estimated implicit price obtained from the regression for the county in which the individual lived. The sample size was 290. Other explanatory variables were number of trips and income. Figure 1 illustrates this regression. Scattered along a horizontal price line (say, price = 247 miles) are all the salmon anglers in some county (Washington) who were in the sample. They went to different places and each place had a different catch per trip.

Equation (7) represents the simplest second-stage regression estimating the demand for success:

$$\begin{aligned} \text{Catch per hour} = {} & 0.14 - 0.2 \times 10^{-4}(\text{PSAL}) - 0.14 \times 10^{-2} \text{ trips (N)} \\ & \quad (3.5) \quad (-2.54) \qquad\qquad (-1.65) \\ & + 0.34 \times 10^{-6} \text{ INC} \quad \bar{R}^2 = 0.02 \ ; \\ & \quad (0.88) \end{aligned} \tag{7}$$

where PSAL is the price of the success rate in miles.

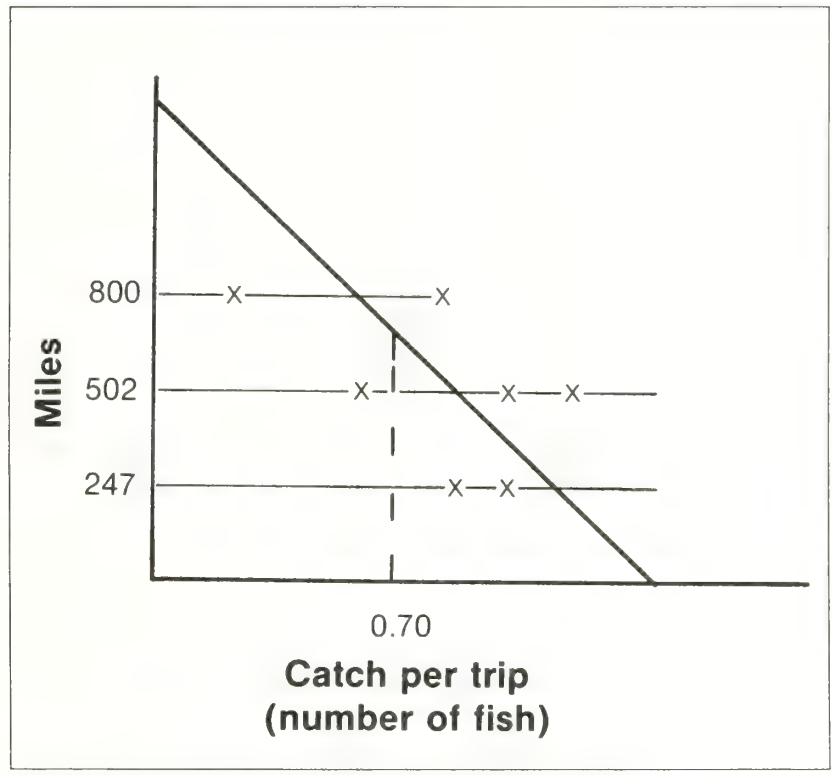


Figure 1—Illustrative second-stage regression where catch per trip is regressed on the estimated implicit price per trip. This represents the demand for fishing success with the price of success measured in miles.

Catch per hour was an unusual dimension to use. I converted to the more usual measure of catch per trip by using an estimate of hours per trip. The analysis showed an average of 3.45 hours per trip, but this was only the actual fishing time. Sorhus (1980) calculated a sample average of 6.8 hours per trip. For comparison with other estimation techniques, the estimates were converted using the ratio of Sorhus' estimate to ours:

$$\left(\frac{6.8}{3.45} = 2.0\right) .$$

The elasticity of demand from (7), evaluated at a mean catch rate per trip of 0.39 by using Sorhus' estimate of 6.8 hours per trip, was 0.18—twice the estimate obtained by using 3.45 hours per trip. This seemed a very inelastic demand. If it is true, or nearly so, then studies computing a constant value of success (as compared to computing a value that is a function of success) will be greatly in error except at the mean. Practically speaking, it means that such studies will badly underestimate the economic losses resulting from success-reducing actions and badly overestimate benefits from success-improving actions.

Taking the inverse of (7), converting to catch per trip, and suppressing the other independent variable yields:

$$\text{PSAL} = \text{constant} - 7{,}245\ \text{catch/trip} , \qquad (8)$$

when the Sorhus estimate of 6.8 hours per trip is used (the slope coefficient is 14,490 if hours per trip is 3.45). Equation (8) is illustrated in figure 1.

The sample mean catch per trip was 0.39.[7] I cannot explain this very low rate of success. By using data from the Oregon Department of Fish and Wildlife, I estimated ocean catch per trip to be 1.03 and freshwater catch per trip to be 0.30. Our sample was 58 percent ocean trips and 42 percent river trips. Applying these weights to the respective success estimates from the Oregon Department of Fish and Wildlife yielded a catch per trip of 0.70, which was 2.4 times greater than the sample mean. As a practical matter, this unresolved discrepancy created a great range in the value estimates.

The sample mean PSAL was 502 miles.[8] This means that Oregon salmon anglers in this sample went ("paid") an average of 351 miles to catch one salmon:

$$\frac{502}{\text{fish}} \times 0.70 \frac{\text{fish}}{\text{trip}} = 351 \text{ .}$$

Consumer surplus (CS) evaluated at the mean catch per trip is:

$$CS = \int_0^{\bar{Q}} f(\bar{Q})dQ - \bar{Q}f(\bar{Q}) = \frac{-\alpha_1 \bar{Q}^2}{2} ; \qquad (9)$$

where $\alpha_1 = 7{,}245$,

$\bar{Q}$ = sample mean catch per trip (0.39 or 0.70), and

$f(Q)$ = the inverse of the demand function in (8).

Thus, the consumer surplus was either 550 or 1,773 miles per trip or, respectively, $55 or $177 per trip at $0.10 per mile. This seemed a bit high, unless the $0.10 mile included some measure of opportunity cost of time. Although $0.10 per mile was a reasonable estimate of out-of-pocket expenses, perhaps expenses should be adjusted by the number of anglers in the car. Assuming that expenses are shared, either in fact or in effect by each individual taking a turn at providing transportation, seems reasonable.

With equation (9), the average value per fish can be computed for any catch. Evaluated at the mean, the average value of a salmon is:

$$CS/\bar{Q} = -\alpha_1 Q/2 \text{ .}$$

The average value per fish is about $141 or $254 at $0.10 per mile and 0.39 or 0.7 catch per trip, respectively. I think this is a high range.

---

[7] Total sample catch equals 428 and total sample trips equals 1,094.

[8] This and other average values are shown in the appendix to this chapter.

The marginal consumer surplus (MCS) addresses the amount a salmon angler would pay to have improved success at a fishing site; for example, what is the value per trip if success per trip increases by 10 percent? From (9):

$$MCS = \Delta CS = - \bar{Q}f'(\bar{Q})\Delta Q \ . \qquad (10)$$

At the average of 0.39 or 0.70 fish per trip, salmon anglers would pay 113 or 355 round trip miles—$11.30 or $35.50 per trip at $0.10 per mile—for an average improvement in fish catch of 10 percent.

After the demand for catch per trip is estimated, the marginal consumer surplus at a level of success can be computed by using equations (8) and (10). The value of improving a site yielding a success rate 25 percent below average can thus be compared with the cost of improvement. Or the value of improving a site yielding a high catch per trip can be compared with the cost of improvement.

The demand equation just discussed had a simple estimate of price. Price was measured in marginal miles. The advantage of such a formulation is that the user may select any unit of mileage cost. For example, if the opportunity cost of time is believed to be 30 percent of the wage rate after taxes and the average speed of traveling is 40 mph, this is equivalent to adding about $0.06 per mile to out-of-pocket mileage costs.[9]

Caution should be taken with the dependent variable in the demand equation, catch per trip. Many of the anglers in the sample fished at more than one site. Catch per trip for each individual was computed as the average of catch per trip for each of the sites visited by that individual. Strictly speaking, it is the level of success for nowhere in particular. This is just an abstract characteristic of all averages.

The averaging is necessary to circumvent pseudoirrational behavior. When anglers face a fixed and constant unit price for one characteristic, success, each should choose the one site and number of trips to that site that maximizes utility. With x characteristics, there are x sites at most that an angler could visit. But, by the design of the applied model, each angler is restricted to one site no matter how many characteristics there are. Models capturing the value of only one characteristic, such as success, by using data from individuals visiting more than one site, are logically inconsistent.

Anglers choose different sites because they have different amounts of time available during different weeks or because one trip is for a family outing and another is with fishing cronies. If we do not structure a questionnaire to obtain these distinctions, however, we cannot explain why multiple sites are chosen; a real possibility of making inappropriate policy decisions exists. The estimates might show that increasing the density of salmon at one-fish-per-day sites is beneficial—where the one-fish node is an average of better and worse sites actually visited. In fact, densities should perhaps be augmented at the sites hidden by the averaging process, not at the one-fish-per-day site.

---

[9] The average annual gross income in the sample was about $18,000. At a 30-percent tax rate and 2,000 hours worked per year, the net wage rate was $6.30 per hour.

Table 1—Demand equations for success (catch per hour) under four alternative specifications

	Linear		Log-log					
Item	β	t-value	β	t-value	β	t-value	β	t-value
PSAL			-0.087	-3.69				
PSA	-0.48×10^{-4}				-0.08	-3.58		
PSAF							-0.14	-2.77
N	$-.14 \times 10^{-2}$	-1.64	-.106	-1.36	-.11	-1.35	-.11	-1.42
INC	$.61 \times 10^{-6}$	1.52	.063	.57	.11	1.00	.10	.84
Constant	.13	13.89	-2.54	-2.39	-3.12	-2.90	-2.60	-2.41
$\bar{R}^2$	.17		.04		.04		.03	

The danger discussed above arises when the method is used for valuing characteristics of a location. The problem is inconsequential when only average values are desired, and in this case, no particular reason exists to use a hedonic technique that is expensive because it uncovers a marginal function; a cheaper technique would uncover a constant, the average.

Table 1 summarizes regressions involving various estimates of implicit prices and both a linear and double-log specification. The PSA variable is the dollar measure of miles and includes the marginal opportunity cost of time at 30 percent of the hourly wage rate.[10] The PSAF is the sum of PSA and the marginal fixed cost of a trip, which varies with catch per trip.[11] The fixed cost includes expenditures on guide service, bait, rental equipment, boat launching, and gas for a boat. It excludes camping and lodging fees and food and drink expenses because these do not vary with catch per trip. Even though value is obtained from these latter expenditures, there is little reason for believing that the marginal utility of food varies with marginal catch.

In linear form, the slope coefficients were the same in regressions with the implicit price using distance in money terms (PSA) and those with the price including the fixed cost, which varies with success (PSAF).[12] The logarithmic form of the regression using PSA produced a low estimate of the elasticity of demand (0.08). Apart from a higher elasticity of demand (0.14 vs. 0.08), the log-log demand function with PSAF closely resembled the demand function with PSA. In none of the regressions was income or number of trips statistically significant. Cross-sectional analysis usually does not produce a very high R^2, and the R^2 in all the regressions was very small.

---

[10] $$PSA = \left[0.3 \left(\frac{\text{annual income}}{2000 \text{ hr}}\right)/\text{mph} + TC\right] \cdot PSAL,$$

where $\text{mph} = \begin{cases} 40 \text{ if car or pickup} \\ 35 \text{ if motor home} \end{cases}$, and

$TC = \begin{cases} \$0.0975 \text{ if car or pickup} \\ \$0.1160 \text{ if motor home or camper} \end{cases}$.

[11] The equation for the per-capita fixed cost (PSAF) is:

$$PSAF = \underset{(5.86)}{3.59} + \underset{(2.86)}{12.11} \text{ catch-per hour} \qquad \bar{R}^2 = 0.01 .$$

[12] One variable is the linear transformation of the other, and PSAF = 12.11 + PSA.

The number of trips (N) taken by a salmon angler was assumed to be a choice variable, so a corresponding demand function for trips was needed. The following semi-log specification had the most desirable statistical properties:

$$\ln N = 1.12 - 0.63 \times 10^{-3}\text{PSA} - 1.71 \text{ catch per trip} \qquad (11)$$
$$(8.67) \quad (-2.39) \qquad (-2.57)$$

$$+ 0.35 \times 10^{-5}\text{INC} \quad \bar{R}^2 = 0.03 \ ;$$
$$(0.76)$$

where PSA is the marginal price of success each person faces (see footnote 10), and INC is income. Income was not significant but the other variables were. It seemed reasonable that trips should vary inversely with the price of fishing success, but it was less obvious why trips fell as the quality of trip (catch per hour) rose. A quality increase raised the total cost of a trip even when the price per unit of quality was constant. In this model, total cost per trip was the product of price of a characteristic and the level of the characteristic (plus a constant). Trips should fall when the total cost of a trip rises.

Conclusions

Applying a hedonic travel cost to the Oregon sport salmon-fishing data was an experiment with limited success. For the technique to be empirically successful, the number of origins of anglers selected had to be large enough to produce an adequate sample size in the second-stage regression. The nature of the data collected limited us to only 14 sample origins. The original sample was designed with other purposes in mind.

The number of people in each origin had to be large enough and go to different places with sufficient variation in the level of the characteristic to permit a reasonable chance of obtaining a set of regression coefficients for each origin selected. I had neither enough people nor enough different locations to feel confident about the estimates. Care in sample design will have to be taken in future applications of hedonic travel-cost methods.

By using the sample-catch data, I estimated the average value of a trip to be $55 and the average value of a sport-caught salmon at $141. I used the State's catch data to estimate the value of a trip to be $177 and the value of catch to be $254. These estimates were most comparable to Gibbs' estimates (see chapter 4) from unadjusted individual observations. Applying the proportions of freshwater and ocean anglers in my sample to Gibbs' values yielded a value per trip of $141.[13]

In W. Brown's study (see chapter 3), the value of salmon caught in fresh water is about $90, and the value of salmon caught in the ocean is about $50; the precise cost depends on whether actual or predicted trips are used and on the definition of zones. These values are substantially less than my estimates. Because the models were not nested, it was not possible to give a definitive explanation for the difference. Gibbs' study shows that a major difference comes from choosing between individual and per-capita data; this causes differences as small as 70 percent and as large as 300 percent. My results lacked a strong statistical foundation because of the small sample size.

---

[13] Weights of 42 and 58 percent, respectively, were applied to a value of $61 per day of freshwater fishing and a value of $199 per day of ocean fishing.

W. Brown obtained an estimate of about $90 per freshwater-caught salmon when time was valued at one-third the wage rate or about $3.00 per hour. He also assumed that cars travel at 45 mph, so this amounts to an additional $0.07 per mile. Introducing time costs in this way increases the value of salmon about 15 percent, from $78 to $90. The price of a mile entered my valuation estimates linearly. Increasing the mileage cost from $0.10 to $0.17 to incorporate the opportunity cost of time caused an increase of 70 percent; it increased the trip and catch values in my study by 70 percent.

Time costs play a less significant role in W. Brown's travel-cost study because his base costs per mile included food and lodging expenses, which were not included in the hedonic approach. In the hedonic approach, food and lodging expenditures were assumed to provide characteristics, such as being well fed, that have utility. Because I could not measure these characteristics, I decided less error would be caused by omitting them. Including food and lodging expenditures in the travel-cost study should increase the value of salmon compared to the results when such costs are excluded; moreover, excluding substitute sites should increase the value of salmon relative to an analysis that includes substitutes, such as the hedonic method. On both these counts, the hedonic-based values should be lower, other things being equal, than the travel-cost-based values. They were not. Probably the best next step is to design a study suitable for the analysis of both the travel-cost and the multimarket-hedonic approaches.

Literature Cited

Burt, Oscar D.; Brewer, Durwood. 1971. Estimation of net social benefits from outdoor recreation. Econometrica. 39: 813-27.

Sorhus, Colin N. 1980. Estimated expenditures by sport anglers and net economic values of salmon and steelhead for specified fisheries in the Pacific Northwest. Corvallis, OR: Oregon State University. 142 p. Ph.D. thesis.

Appendix

Sample statistics

Total salmon catch	428
Total trips	1,094
Mean PSA	170.45
Mean PSAL	501.76
Mean N	3.77
Mean PSAF	182.56
Mean INC	186.76
Mean PCA	46.23
Mean PCAF	58.34
Total hours	3,777

Chapter 8: Further Comparison of Results From Three Recreation-Valuation Methods

Elizabeth J. Strong and Darrell L. Hueth[1]

We had two objectives for this final chapter. One was to determine whether results obtained from TC, HTC, and HP models were comparable and under what circumstances. The specific results considered were estimates of average values of recreational commodities, such as a fishing experience and a sport-caught fish. The second purpose was to compare the results from the four empirical studies of salmon and steelhead fishing in Oregon presented in chapters 3 through 7. At first glance, these empirical models appeared to be comparable because they were all applied to data on salmon and steelhead fishing activities that came from the same source (that is, the 1977 mail survey of Oregon anglers). Furthermore, each of the models described the behavior of a representative individual in terms of the demand for sport-fishing at a typical site. Closer inspection of these models revealed that they were not directly comparable. Many reasons explain why the commodity value estimates from the different empirical models were not similar.

[1] ELIZABETH J. STRONG was research assistant, Oregon State University, Department of Agricultural and Resource Economics, Corvallis, OR 97331; she is currently resource economist, Yuma, AZ. DARRELL L. HUETH was professor, Oregon State University, Department of Agricultural and Resource Economics, Corvallis, OR 97331; he is currently professor, University of Maryland, Department of Agricultural and Resource Economics, College Park, MD 29742.

Comparability of Results

All three methods can in theory be used to estimate the values of a fishing experience and a sport-caught fish. Whether the unit values obtained from the different models are directly comparable depends on how each model was constructed and on how the values were determined. Constructing a model refers to the variables used, how the variables were defined, and the types of observations used to estimate the model. The valuation procedure refers to the market(s) where benefits were evaluated and whether the procedure provided a marginal or an average value estimate.

We assume here that the common variables in each model were defined in the same way. In particular, we assume that the price of a visit in each model was based on the same types of expenditures. We also assume that the same types of observations were used to estimate each model; for example, we could assume that individual observations of fishing activities were used to estimate each model. If this were true, each model would then describe the behavior of a representative salmon or steelhead angler at a typical site. Under these assumptions, the three models differed mainly in the behavioral and technical assumptions they were based on and in the procedures used to determine the nonmarket value of recreational commodities.

Value of a Fishing Experience

Each of the methods provided estimates of the average value of a fishing experience. This value was assumed to measure the benefits a representative angler derived from a fishing experience at a typical site. This average benefit measure was assumed to include values of any quality characteristics of the experience that were perceived by anglers. The only quality characteristic considered here is the fishing success rate.

With the TC and HTC methods, similar procedures were used to obtain estimates of the average value of a fishing experience. The consumer-surplus area under the demand curve and above the mean price was divided by number of visits made to a single site. These average values probably will not differ significantly between the two methods.

With the HP method, a comparable value per fishing experience was estimated by calculating total benefits in both the fishing trips and fish-catch markets for a representative angler and dividing this benefit measure by the mean number of visits made to a single site. If implicit prices in these markets are fixed and based on the same set of market goods and time allotments as are the prices per visit used in the TC and HTC models, then the value estimates obtained from the latter two models should not differ significantly from the value obtained from the HP model. The main difference between using an HP model with fixed implicit prices and using either the TC or the HTC model to estimate the average value of a fishing experience is that the HP model explicitly accounts for the interrelatedness of the fishing trips and fish-catch commodities. The degree of interrelatedness is indicated by the cross-price effects between the two commodities. The relation between these two commodities can significantly affect the estimated value of a fishing experience.

Value of a Sport-Caught Fish

A different procedure was used in each of the three methods to estimate the value of a sport-caught fish. With the TC method, the two-stage procedure of first estimating recreational benefits and then specifying a relationship between total benefits and fish catch was used. The marginal value of a fish was roughly equal to the increase in total benefits (as calculated in the visits market) resulting from a one-unit increase in the number of fish caught. An estimate of the average value was determined by dividing total benefits in the visits market by the number of fish caught. This procedure for obtaining an average value and the two-stage procedure for obtaining a marginal value (using a linearly homogeneous function) attributed the total utility derived from the fishing experience to the fish catch per visit. If other attributes of a fishing experience, besides the fish catch, give the angler some utility satisfaction, then these two procedures may provide upwardly biased value estimates.

With the HTC method, the value of a sport-caught fish can be estimated in the fish-catch-rate market rather than in the visits market as was done in the TC method. The implicit price of the catch rate was defined as the marginal change in the price per visit with respect to a one-unit increase in the catch rate. If the constant term were zero in the hedonic price function, then the total variation in the price per visit for different sites would be allocated to the implicit price of the catch rate. If this were true, then we would expect the marginal value of a fish from the HTC model to be similar to the value obtained from the TC model, in which there was a linearly homogeneous relationship between benefits and fish catch. Otherwise, the estimated marginal value of a fish from the HTC model would be expected to be lower than the value from the TC model because part of the price variation in the HTC model would be assigned to the other utility-yielding attributes of the fishing experience. The same relationship between the two models held for average values per fish. An average value was obtained from the HTC model by dividing total benefits in the catch-rate market for a representative angler by the mean catch rate.

Like the HTC model, the HP model provided an estimate of the average value of a sport-caught fish on the basis of benefits measured in the fish-catch-rate market alone. Here, though, the implicit price of a sport-caught fish was determined solely on the basis of the market goods and time allotments used for catching fish. Thus, this implicit price might not be the same as the implicit price used in the HTC model. If they were similar, then similar average-value estimates would be expected from both models.

Because the average value provided by the HP model is based only on benefits measured in the catch-rate market, it was expected to be lower than the average value obtained from the TC model. A necessary condition for these values to be similar is that the HP model be specified such that the demand for trips falls to zero when the implicit price of fish catch reaches the point where there is zero demand for fish catch. This condition means that the average per-fish value can be calculated by dividing the benefits of a recreational experience for a representative angler at a typical site by the mean catch rate. A similar procedure (shown earlier) was used to obtain an average value estimate from the TC model.

Comparison of Some of the Empirical Results

Differences in definitions of variables and in the types of observations used in the various empirical models presented in chapters 3 through 7 made the results difficult to compare directly. By adjusting some of the results, however, we obtained average-value estimates that could be compared. We first present the average values of a salmon-fishing experience and a sport-caught salmon as obtained from the TC and HTC models. Then, we present average values for steelhead fishing experiences and sport-caught steelhead as obtained from the TC model and the HP model. Reasons for not expecting the value estimates to be similar are highlighted in the following discussions.

Average Values for Salmon Fishing

In chapter 3, several TC demand models were presented. The zonal-average method and the adjusted individual-observation method were applied to separate sets of data on freshwater and ocean salmon fishing. Chapter 4 presented two more TC demand models for freshwater and ocean salmon fishing. These models were estimated by using the unadjusted individual-observation approach. Because individual observations were also used in applying the HTC method presented in chapter 7, the results from that method should probably be compared with the results from the TC models based on unadjusted individual observations (from chapter 4). The data on freshwater and ocean salmon angling were combined in the HTC method to form a single data file on salmon fishing in general. To compare the results from chapters 4 and 7, a weighted average of the values for freshwater and ocean salmon must first be obtained from the two TC models. The weights of 0.42 and 0.58 were used for freshwater and ocean salmon, respectively. These weights were based on the sample proportions made up of each type of fishing activity.

Table 1 presents the average values of a salmon-fishing experience and of a sport-caught salmon that were obtained from both the TC and the HTC models. The values for the TC model were determined by taking a weighted average of the values obtained from the two TC models that were based on unadjusted individual observations. The data on fish catch used to estimate the average value of a fish in these two models were obtained from the Oregon Department of Fish and Wildlife. The average values shown for the HTC model were estimated using data on fish catch per visit that were also from the Oregon Department of Fish and Wildlife.

Table 1—Average per-unit values as estimated from the TC and HTC models for salmon fishing

Commodity	Model	
	TC	HTC
	Dollars	
Fishing experience	141	177
Sport-caught fish	248	254

The values obtained from the TC model were coincidentally similar to their counterparts from the HTC model. These similarities were not expected, however, for two reasons. First, the price of a visit was defined differently in each of the models. The price used in the TC model was defined as the sum of the costs of operating a vehicle, food and lodging costs incurred while traveling, and the opportunity cost of travel time. The price used in the HTC model was equal to the costs of merely operating a vehicle. Second, different procedures were used to derive the average values. The average value of a fishing experience was obtained from the TC model by calculating total benefits in the visits market for all sites and dividing this consumer surplus measure by the total visits made. The HTC model was used differently to estimate the average value of a fishing experience at a typical site; that is, the total consumer surplus for a representative angler was calculated in the catch-per-trip market. This benefit measure was assumed to represent the total benefits derived by the angler from the fishing experience. To use this procedure, however, it must be assumed that if the catch per trip were zero, then the angler would derive no utility from the fishing experience. Because a utility function was not specified in chapter 7, this hypothesis could not be tested empirically. If other quality characteristics of a fishing experience would give the angler utility even if no fish were caught, then the average value of a fishing experience would probably be understated by the method used in chapter 7.

Both of the factors mentioned above presumably make the value estimates from the HTC model lower than those from the TC model. This was not true with the values presented in the first line of table 1. Perhaps part of the reason is the model specification used in chapter 7, in which the demand for the catch rate at a given site was specified as a function of the implicit price of the catch rate, income, and the number of fishing trips to the site. Because the number of fishing trips was an endogenous variable, a specification bias would clearly occur. The dependency of fishing trips on the implicit price of the catch rate can also lead to biased parameter estimates in this demand equation. A simultaneous-equations technique can be used to determine whether a significant bias resulted from using single-equation techniques to estimate both the demand equation for the catch rate and the demand equation for the number of fishing trips.

Any biases resulting from a single-equation regression technique would have affected the estimated average values from the HTC model shown in table 1. The average value of a sport-caught salmon was determined by dividing total benefits in the catch-rate market for a representative angler by the average catch per trip. The average value obtained from the TC model was determined by dividing total consumer surplus associated with fishing experiences across all sites by total fish catch. This procedure was equivalent to calculating total consumer surplus in the visits market of the HTC model and dividing by the total fish catch. Even if this procedure were used with the HTC model, the average value obtained would not be expected to be similar to the value obtained from the TC model because of the differences in the price-per-visit variables used in each of the empirical models.

Average Values for Steelhead Fishing

The TC and HP methods were both applied to data on steelhead fishing in Oregon. The two empirical models for steelhead fishing presented in chapters 3 and 6 were not directly comparable, however, because the TC model in chapter 3 was estimated with zonal observations on visits per capita, and the HP model in chapter 6 was estimated with individual observations of participating steelhead anglers. Also, the prices were defined differently in each of these two models.

The HP model divides the fishing experience into two commodities with different implicit prices—the fishing trip and the fish catch per trip. The single price variable used in the TC model should thus be defined on the same basis as both of the prices in the HP model to obtain comparable values of a fishing experience from the two models. The implicit price of a fishing trip in the HP model for steelhead fishing was based on the cost of operating a vehicle, the cost of food and lodging while traveling, and the opportunity cost of travel time. These are the same expenditures included in the price variable used in the TC model. To provide comparable results for the average value of a fishing experience, however, this latter price variable must also include expenditures on fishing supplies and fishing time costs, because these on-site costs were used to determine the implicit price of a sport-caught fish in the HP model.

When the two factors discussed above are considered, the average value of a fishing experience from the TC model would be expected to be lower than the average value from the HP model. That this was not true with the values presented in table 2 is surprising. Perhaps this was due partly to the TC model being applied to data from only 21 rivers, while the HP model was applied to these same data plus data from 9 additional rivers. These 9 additional rivers were apparently less popular than the other 21, so their inclusion could have caused a lower value for an average fishing experience.

Some reasonable explanations exist for the remarkable difference between values from the TC and HP models for sport-caught steelhead (table 2). First, the fish-catch data used to determine an average value from the TC model were from the Oregon Department of Fish and Wildlife, but the data used to construct the fish-catch variable in the HP model were from the angler questionnaires. The Oregon Department of Fish and Wildlife data implied an average catch per trip of 0.24, whereas the angler survey data implied a much higher average catch per trip of 0.81. It was therefore not surprising that the HP model provided a considerably lower estimate of the average value of a fish than did the TC model.

Table 2—Average per-unit values as estimated from the TC and HP models for steelhead fishing

Commodity	Model	
	TC	HP[a]
	Dollars	
Fishing experience	27	21
Sport-caught fish	115	25

[a] The means of compensating and equivalent variation estimates for a representative angler.

We used the above two estimates of average catch per trip to convert the $25-value per fish to something more comparable with the $117 obtained from the TC model. By multiplying $25 by 0.81 and dividing the product (value of fish catch per visit) by 0.24, we obtained a revised per-fish value of $84, which is much closer to the $115 obtained from the TC model. Two possible reasons why this revised value is still lower than the value obtained from the TC model are that (1) the average value obtained from the HP model was based only on the benefits associated with catching fish, rather than on the benefits associated with the whole fishing experience; and (2) including the 9 additional rivers in the sample for the HP model may have resulted in a lower per-fish value as compared with the value obtained using data across the subset of 21 rivers.

Conclusion

The clear comparison among methods that was hoped for in this study was only partially achieved because the three methods were not used to obtain the same values. And the results that could be compared were not expected to be similar because of different definitions and measurement techniques used. These differences complicated the comparison of value estimates derived from the various models by making it difficult to account for differences in value estimates on theoretical grounds.

Whereas all three methods can be shown to be derived from a constrained utility-maximization problem, the application of each requires data on different variables and optimally a different experimental design. For example, the successful application of the zonal travel-cost method was enhanced by an experimental design that ensured a large number of participants from many zones at a particular site, whereas the successful application of the hedonic travel-cost model required recreationists from a particular zone visiting a large number of sites at various distances from that origin. For both travel-cost and hedonic travel-cost methods, the cost of a trip was equal to the distance multiplied by some estimated cost of transportation per mile (which may or may not have included the time component of travel). The household-production method would have had improved results if independent data had been available on time taken to travel to the site and travel expenditures. It was useful, for the household-production method, to have data on several fishing sites visited by anglers from different distances.

The questionnaire for this study was designed with only the travel-cost model in mind, and many shortcomings were found when this data base was used to apply both the hedonic travel-cost and the household-production methods. Indeed, one major result of this work was finding that a significant amount of preplanning in questionnaire design is necessary if a single data base will be used to estimate values by more than one method.

U.S. GOVERNMENT PRINTING OFFICE:1988-591-132/82019

Hueth, Darrell L.; Strong, Elizabeth J.; Fight, Roger D., tech. eds. 1988.
Sport fishing: a comparison of three indirect methods for estimating benefits. Res. Pap. PNW-RP-395. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station; 99 p.

Three market-based methods for estimating values of sport fishing were compared by using a common data base. The three approaches were the travel-cost method, the hedonic travel-cost method, and the household-production method. A theoretical comparison of the resulting values showed that the results were not fully comparable in several ways. The comparison of empirical results showed differences in values not easily accounted for on theoretical grounds. The data base was not designed to provide data for all three methods, and some of the resulting models explain only a small proportion of the variation.

Keywords: Recreational value, fishing, models.

The **Forest Service** of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives—as directed by Congress—to provide increasingly greater service to a growing Nation.

The U.S. Department of Agriculture is an Equal Opportunity Employer. Applicants for all Department programs will be given equal consideration without regard to age, race, color, sex, religion, or national origin.

U.S. Department of Agriculture
Pacific Northwest Research Station
319 S.W. Pine Street
P.O. Box 3890
Portland, Oregon 97208

BULK RATE
POSTAGE +
FEES PAID
USDA-FS
PERMIT No. G-40

Official Business
Penalty for Private Use, $300

do NOT detach label

Clemson University
3 1604 010 144 014

DATE DUE

OCT 18 1995	
APR 20 1996 APR 19 '96	
RT/CO APR 22 '99 RET'D	
APR 10 1999	

DEMCO, INC. 38-2931

INFORMATION CONSERVATION, INC.